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RESEARCH PAPER

Spatio-temporal analysis of urban growth from remote sensing data in Bandar Abbas city, Iran

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Abstract Today, urban growth is a multidimensional spatial and population process in which cities and urban settlements are considered as centers of population focus owing to their specific economic and social features, which form a vital component in the development of human societies. The analysis of urban growth using spatial and attribute data of the past and present, is regarded as one of the basic requirements of urban geographical studies, future planning as well as the establishment of political policies for urban development. Mapping, modeling, and measurements of urban growth can be analyzed using GIS and remote sensing-based statistical models. In the present study, the aerial photos and satellite images of 5 periods, namely (1956–1965, 1965–1975, 1975–1987, 1987–2001, 2001–2012) were used to determine the process of expansion of the urban boundary of Bandar Abbas. Here, in order to identify the process of expanding urban boundaries with time, the circular administrative border of the city of Bandar Abbas, was divided into 32 different geographical directions. Here, Pearson's Chi-square distribution as well as Shannon's entropy is used in calculating the degree of freedom and the degree of sprawl for the analysis of growth and development of the cities. In addition to these models, the degree-of-goodness was also used for combining these models in the measurement and determination of urban growth. In this way, it was found that the city of Bandar Abbas has a high degree of freedom and degree of sprawl, and a negative degree of goodness in urban growth. Regardless of the results achieved, the current study indicates the capability of aerial photos and satellite imagery in the effectiveness of spatio-statistical models of urban geographical studies.

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1. Introduction

Urban growth can be regarded as the process of developing urban centers. Being an all-encompassing process, urban growth entails a wide range of concepts as well. The urban

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development process should be discussed based on its history and effective factors such as environmental, physical, social and economic factors over time. During the past two centuries, we have been witnessing the expansion of large cities and the growth of the space under their spatial influence. This in most cases is due to the changes in functional structures over time in the rural areas and the corresponding changing pattern of life of residents, resulting in the formation of new urban areas (Clark, 1982). Urban growth is often a spatial population process, and usually indicates the significant role played by towns and cities in the distribution of population of a given socioeconomic setup. This process usually takes place as a result of changes in the distribution of the population from the villages and the countryside, as the origin of the formation of human society, to cities and urban residences. In contrast, urbanization is regarded as a spatial and social process resulting in a change in the relationship between human societies and social behaviors in various dimensions. This process deals with the complex transformations in the life styles of human societies, which have a direct impact on the urban communities. Spatial integration and dynamicity of urban growth are significant issues in the studies of contemporary cities. In recent years, several studies have been done with regard to population distribution, social systems and urbanization (Batty and Howes, 2001; Belkina, 2007; Herold et al., 2002; Martinuzzi et al., 2007; Rafiee et al., 2009; Yanos, 2007; Yeh and Li, 2001; Taha, 2014). From the review of the relevant literature, it can be generally deduced that the ever increasing rise in the urban land use has various ramifications. These include the rise in both security and quality of the residences, improved employment opportunities as well as economic growth. Also documented is the rise in environmental degradation and disturbances to the natural ecosystem, as well as rising environmental pollution, loss of natural resources and increase in temperature levels. The sprouting of unofficial residences and decrease in available land for agriculture have also been associated with increasing land use. Finally, deforestation, destruction of the vegetation cover and shortage in food supply were also reported as some of the emerging problems of increasing urban land use (Barnes et al., 2001; Hedblom and Soderstrom, 2008; Herold et al., 2003; Lassila, 1999; Litman, 2007; Muñiz et al., 2007; Weng, 2001; Iqbal and Khan, 2014). Furthermore, the literature review shows that the concentration of human communities is one of the effective factors of urban growth. However, in many aspects of the process, the growth has been generally uncontrolled and dispersed, which constitutes a vital obstacle to the process of sustainable regional development. Today, the unruly urban growth rate has become a worrying subject (Al-Awadhi, 2007; Kumar et al., 2007), especially in the developing countries, such as Iran. In Iran, the city of Bandar Abbas is facing a lot of hindrances to the development of its urban boundary because of the natural limits in the North (rocky cliffs) and South (coastal areas) as well as the physical limits in the East and West (military lands). In recent years Bandar Abbas city has encountered accelerated and wide spread urban growth due to its strategic location, proximity to main ports of import and export and existence of several industrial zones near it. According to first performed census in Iran in 1956, the number of Iran's cities was 201 and the ratio of urban population to whole population was 29%. In 2012 the number of cities became 1331 and the ratio of urban population became 70% of whole population (Farhoudi et al., 2009; Iranian Statistic Center, 2012). UN (2014) projections demonstrate that Iranian urban population will reach to 80% of whole population by 2020. Large cities such as Isfahan, Mashhad and Tehran are experiencing transfer of urban growth procedure from compressed form to sprawl form (Zanganeh et al., 2011). In some medium and small cities this procedure is rapidly expanding dependent on their location and specific characteristics. Bandar Abbas city is a large city whose physical growth and land cover/use change have been rapid during recent years. Since definition of counties and urban hierarchies are diverse in different countries, in this study urban sprawl and process of land use/cover change in Bandar Abbas city is investigated based on exploiting urban hierarchies in Iran.

Therefore, in the analysis of the growth of cities, both the pattern and process of development are considered, in order to easily afford an advanced understanding of the rapidly changing urban landscape. For this to be achieved, the following need to be comprehensively ascertained: (i) the population growth rate of the given urban center, (ii) spatial configuration of growth. (iii) The difference between actual and the forecasted growth levels. (iv) The difference between the spatial and temporal growth patterns. (v) A survey of the magnitude of the space and size dimensions of the growth. Using this analysis method, not only can the past and present be examined, but also the future.

In the recent past, there has been increasing research attention on the use of remote sensing, GIS and photogrammetric data retrieval methods for intelligent navigation, mapping as well as simulation modeling of urban growth. These techniques have also been widely employed in the identification of changes in land use as well as the development and expanding nature of towns and cities (Angel et al., 2005; Bhatta, 2010; Batisani and Yarnal, 2009; Deng et al., 2009; Pathan et al., 1991). With the assistance of the embedded decision-making support features, the GIS has the ability to assess the data generated from remote sensing using multi-agent data evaluation techniques (Fotheringham and Wegener, 2000; Alberti, 2005; Shahi et al., 2015). This technique can make projections into the future using current and past collated data of the phenomena of interest.

Moreover, the use of photogrammetric and satellite data to determine urban growth rate and spatial configuration is reported to be common (Donnay et al., 2001; Herold et al., 2005; Wang et al., 2003), using various statistical parameters of gauging a city's development process (Landis and Zhang, 2000). By using statistical models, the accuracy and error levels are significantly improved in the analysis, which can be used as a quality benchmark in urban studies (Griffith, 1988). Therefore, due to the importance of spatial data for the estimation and measurement in urban related studies, the statistical methods based on the analysis of spatial data for estimation and measurement of urban growth, have been extensively utilized by researchers. For example, Páez and Scott (2004) developed the methods for practically generating the confluence of urban analysis and statistical spatial models. In the study, the authors relied on various spatial and regression based models. Similar works include analysis of the distribution and dispersion of human populations in various residences (Portugali et al., 1997); local, regional, and trans-regional competitions in economic activities (Benati, 1997); the development of infrastructures, transportation and network traffic

(Batty and Xie, 1997); the general growth of the city in terms of per capita and density (Clarke et al., 1997; Pendall, 1999) as well as dynamicity of prospects, as well as the allocation of urban land for various purposes (Batisani and Yarnal, 2009; Batty and Howes, 2001; Cho et al., 2010; Dewan and Yamaguchi, 2009; Serra et al., 2003; Turner, 2007).

Another set of works utilized cellular automata rules to simulate urban phenomena. These include the simulation of processes such as residential development and urban residences (Deadman et al., 1993; Deep and Saklani, 2014); investigations into the varying nature of landscape (Soares et al., 2002); boundary expansion of urban centers (Clark and Hosking, 1986; Belal and Moghanm, 2011; White and Engelen, 2000), and the changes in the use of urban land resource in a specified time period (Li and Yeh, 2002). Also, several statistical-spatial models have been used and analyzed to determine continuity, density, clustering, proximity, nuclearity, and mixed use (Galster et al., 2001). The aim of this study is to analyze urban growth (instead of urban development that includes urbanization) with the use of remote sensing data in the past and present along with the statistical models used in the various spatial and temporal scopes. In the current work, aerial photos together with satellite images in six periods (1956, 1965, 1975, 1987, 2001, and 2011) were used to specify the classes of urban land use and urban sprawl within the study area in the specified time span. Using these data, Pearson's chi-square and Shannon's entropy were applied for data analysis. The statistical model of Person's chi-square specifies the amount of the difference of urban growth in different time periods (Almeida et al., 2005; Bonham-Carter, 1994), which is utilized together with Shannon's entropy model for the determination of the changes in expansion of urban boundaries (Bhatta, 2009c; Kumar et al., 2007; Lata et al., 2001; Li and Yeh, 2004; Sudhira et al., 2004). Nevertheless, from the review of the previous studies, the use of these models has been very limited. These include the work by Almeida et al. (2005) on urban growth, which employed the chi-square and entropy for determining the degree of freedom based on the assessment of the common information. Yeh and Li (2001) have used a variety of forms of entropy model in analyzing the various urban growth-based techniques. Kumar et al. (2007) employed the entropy model for determining the expansion process of cities in a certain period. Similarly, Sudhira et al. (2004) utilized the same method, though based on data from a population census, for analyzing the changes in urban boundaries.

In previous studies done so far, these models have been mainly used for the analysis of urban spatial phenomena such as the process of changes in the form and structure of city, spatial development directions, and land-use changes. In this study, the methods of spatial data analysis used are different from those of the previous studies. This study shows that the statistical models of entropy and chi-square can be used for analyzing the model of urban growth, the process, as well as in measuring the combination of both parameters of the model and process. This is a completely new approach in urban-growth phenomenon studies. Because the chi-square and entropy models have been set in various scales; and that there are different perspectives on the analysis of the process of growth, the model degree-of-goodness is proposed as a new model for integration of the models listed (Bhatta et al., 2010). It should be noted that the aim of the current study is to describe and employ novel techniques for achieving a better understanding of the urban growth phenomenon: both past and current. In the current study, however, simulation of urban growth in the future as well as the cause and consequences of various types of growth of urban boundaries, have not been dealt with. In addition, the analysis of the effects of changing land use during the past periods and the environmental impact, which might be caused by the process of transition of these changes are not addressed. In particular, the study's primary objectives include 1 – to identify and determine the urban development process using Pearson's chi-square and Shannon's entropy tests 2 – to design a new technique of ascertaining the degree-of-goodness for the integration of the two models in a measuring scale. All of the models mentioned are investigated in terms of three main directions: model, process as well as the overall status of the urban growth.

1.1. Study area

Bandar Abbas, the capital of Hormozgan Province, is a commercial port city along Iran's southern coastline facing the Persian Gulf. The study area is located at a latitude of 27°8′ N to 27°15′ N and at a longitude of 56°13′ to 56°22′. It has a land area of approximately 100 km^2 (Fig. 1) and includes four regions and 70 districts. Bandar Abbas is a strategically located city in the narrow Strait of Hormuz, hosting the nation's primary naval base. Geographically, the city is situated 9 m above sea level on a flat land area. For Bandar Abbas, the nearby highland areas are Geno and Pooladi Mountains, which are 17 km and 16 km away, respectively. The River Shoor, which empties itself into the Persian Gulf, is also the closest river to Bandar Abbas. The population of Bandar Abbas was 0.52 million in 2012, and given the present growth rate, it is expected to rise to 0.82 million in 2030. For the benefit of sustainability, urban authorities need to understand the nature of the urban sprawl in Bandar Abbas, its distribution, and the directions it is likely to take in years to come. The most important economic activities in Bandar Abbas include heavy industries (commercial ports, fishing ports, oil and gas refinery, and other industries), which employ about 74% of the active population. The city is a popular tourist destination both domestically and internationally. Given these important qualities of the Bandar Abbas, the city became a source of attraction for not only tourists, but also numerous other Iranians. In this way, Bandar Abbas emerged as the Iranian city with the highest urban land development among cities with over 500,000 inhabitants.

1.2. Data and methodology

The aerial photos of the city of Bandar Abbas at 5 time periods are vertical and panchromatic (Fig. 2). After taking the aerial photos, the photogrammetric operations were done for mosaicking photos and geo-referencing to extract topographic maps. The geo-referencing of the aerial photos is done by using triangulation operations, benchmark points prepared by the mapping organization, and topographic maps. It is worth mentioning that geometric corrections required are done during the operation of the photogrammetry on the photos in order to reduce errors and increase the accuracy of interpretation. Generally, the interpretation of aerial photographs

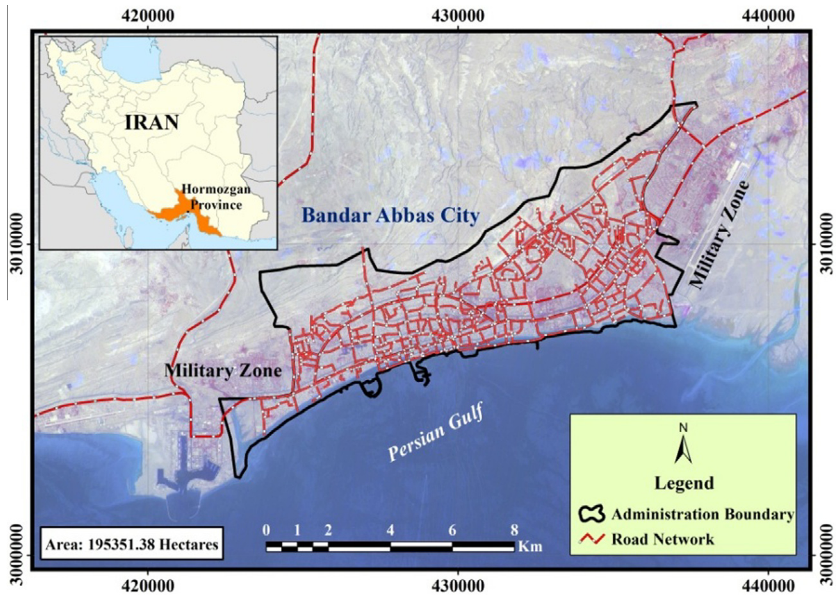

Figure 1 Bandar Abbas location in Iran.

consists of detection and recognition. In this study, features identified and interpreted were digitized directly, using the aerial photographs displayed on the computer screen. The orthophotographs were draped over the DEM, resulting in a 3D visualization. Software packages used for 3D visualization were ERDAS Imagine 2010's Leica Photogrammetry Suite and ESRI-Arc GIS 10. Three dimensional visualization improves the understanding of spatial relationships between image texture and topography, allowing land use features to be observed not only from the normal vertical view, but also at different scales, and different orientations and perspectives (Fig. 2). After the photogrammetry and geo-referencing of aerial photos, the monoscopic view of features is possible, and by using this method, the range of sprawl and growth of cities can be identified and determined.

The spectral details of satellite images are shown in Table 1. Here, the thermal sensor Landsat7 ETM + was not used due to its relatively high spatial resolution compared to other optical bands for the analysis. In addition, unlike the optical bands that make the measurement of the percentage of reflection possible, thermal bands afford data on the radiation temperature. Nevertheless, the presence of these two features results in disorders in the spectrum. As such, the thermal band of the Landsat7 ETM + is removed to afford compatibility between the spectral characteristics of all the sensors. The satellite image of GeoEYe-1 has four color bands with a 1.65 m resolution and a panchromatic band with spatial resolution of 41 cm. Smoothing Filter based Intensity Modulation (SFIM) fusion techniques, were applied to a GeoEye-1 image (Liu, 2000). With the combination of the panchromatic band and color bands, a color image with spatial resolution of 50 cm will be achieved. These images contain an approximate geo-reference and are not in their actual coordinates. Thus, orthorectification was done on the existing images by using the digital elevation model and the topographic map of Bandar Abbas with scale 1:500. This means that control points are chosen for these images on the map and the height of the points are extracted from the digital elevation model. The control points made the relevant image to be located in its actual coordinates. The satellite images used in this study has a standard capability and underwent geometric and radiometric corrections. However, given the different standards and the sources used for the preparation of the image, the overlaying of images is not feasible due to the spatial and spectral resolutions being different. In order to fix this problem, the existing images are recorded again for overlaying based on the accuracy level of their sub-pixels (using root mean square errors of approximately 0.63).

To convert images, the method of nearest-neighbor resampling is used so that the original value of each pixel is maintained. The satellite images and various sensors are different in terms of the spatial resolution. The way to solve this problem is to replace the images with high resolution for comparison with the images with low resolution. However, the process of replacement of images may change the size and value of pixels and the mean between them, or the pixels may be repeated, and the spatial detail reduced or eliminated. Hence, the images are used without changing the pixel dimensions and sizes according to different levels of classification accuracy, spectral, spatial, and radiometric resolution. This method has been selected in order to maintain the spatial detail and numerical value of each pixel. In the next step, the classification of the recorded satellite images is done using the non-parametric classification method for extracting the areas and other features that determine the urban boundary. The non-parametric classification method used in this study for Landsat ETM + and GeoEye-1 image satellite is a parallelepiped and ENVI 5.1 software was used to perform it. The spatial classification of features is important in that it makes possible urban land use classification based on non-normal distribution. The capabilities of urban open spaces are important in that it makes possible homogenous growth and development on the basis of the per capita use, density, and environmental standard in urbanization. It should be noted that if a study is related to the process of growth and development of the city, the urban and non-urban land use classes

Aerial Photos							
Day/Month/Year	Number	Path	Row	Scale	GCPs	RMSE	Spatial Resolution
30-Nov-1956	36	56	302	1:20000	115	0.93	0.93m
6-Dec-1965	43	68	438	1:20000	126	0.96	0.93m
14-Oct-1975	78	74	665	1:15000	250	0.87	0.55m
17-Oct-1987	114	88	459	1:10000	320	0.71	0.53m
17-Dec-2001	118	82	579	1:10000	360	0.71	0.54m

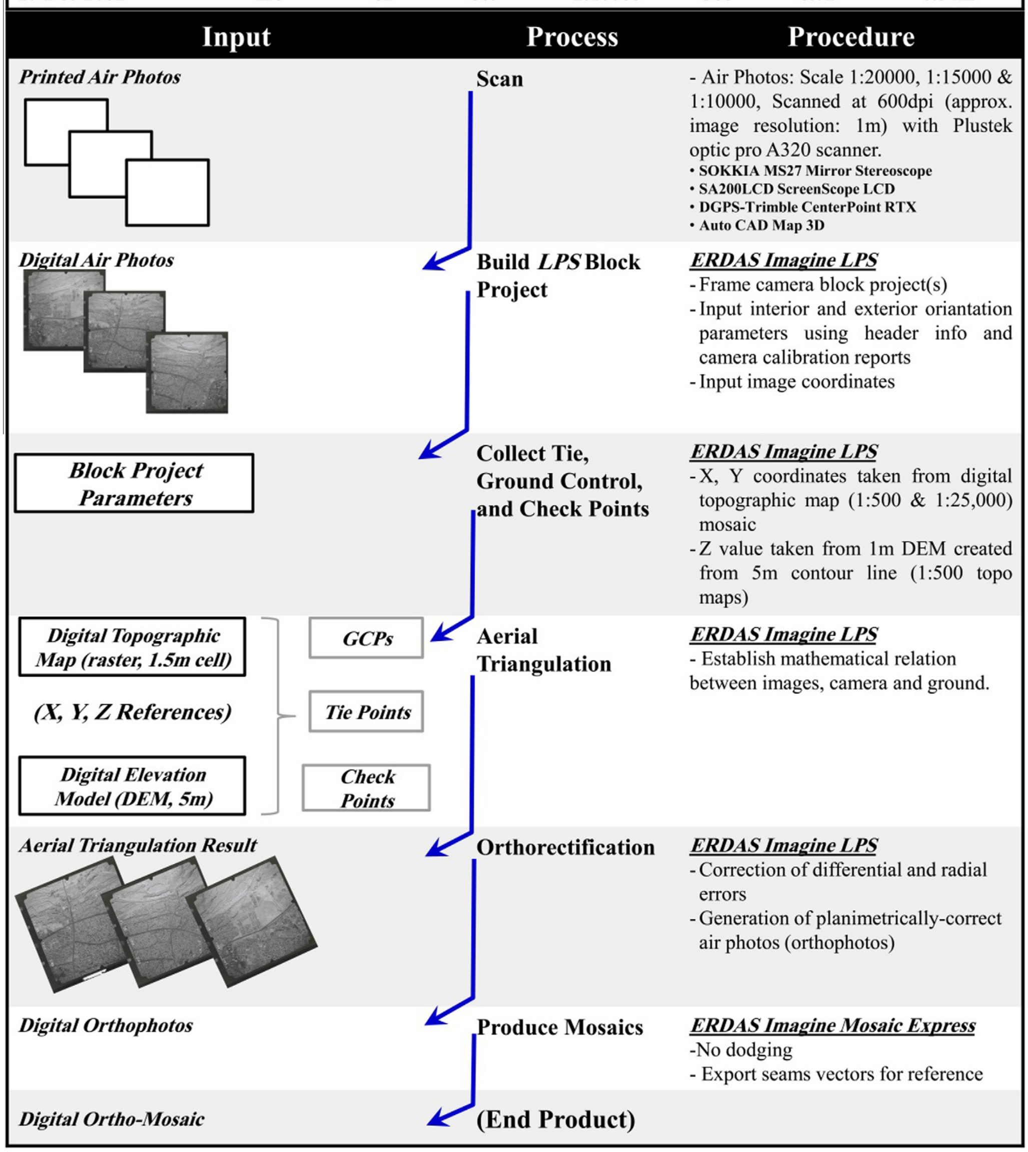

Figure 2 Characteristic of aerial photo and flowchart of digital ortho-mosaic generation (adapted from López Sándoval, 2004).

are considered and their classification using data from aerial photos and remote sensing is adequate and appropriate. After the classification of the images based on land cover, comparison with field reality was conducted using observations and field control.

Topographic maps with scale 1:25,000 (prepared by Iran's mapping organization 1987–1989) and 1:500 (prepared by geography organization 2002–2004) were used to control and analyze the accuracy of the classification of aerial photos and satellite images in the present study. Also, the land use map of Bandar Abbas with a scale of 1:2000 (prepared by the Ministry of Roads and Urban Development – Master Plan 2004–2006) was used to check the accuracy of aerial photos and satellite images in 2001 and 2012. It should be noted that 1300 sampling points were used in the city of Bandar Abbas to compare the land uses of the existing situation and increasing the accuracy of the geo-reference of aerial photos and satellite images.

Table 1 Spectral details of the satellite imagery.

Landsat7 ETM +			GeoEye-1		
Bands	Spectral resolution (μm)	Spatial resolution (m)	Bands	Spectral resolution (nm)	Spatial resolution (m)
1	0.45–0.52	30	Blue	450–520	1.65
2	0.52–0.60	30	Green	520–600	1.65
3	0.63–0.69	30	Red	625–695	1.65
4	0.77–0.90	30	Near infra-red (IR)	760–900	1.65
5	1.55–1.75	30	Panchromatic	450–900	0.41
6	10.40–12.50	60*(30)			
7	2.09–2.35	30			
8	0.52–0.90	15			

The assessment of the level of accuracy was done on each satellite image using 400 pixels, indicating that the overall accuracy of image of the year 2001 is 71% and that of 2012 is 86%. In general, the accuracy attained through the classification of remote sensing data is dependent on a number of considerations. These include the nature of the locations chosen in terms of image quality, size, shape, distribution; the number of repetitions of taking photos of a given area in order to determine the degree of combination of pixels with each other; the performance and spatial resolution of sensors; the method used in classification; the method and accuracy of ground image-takings, etc. Anyway, the investigation of the level of accuracy based on the effective factors mentioned is outside the scope of this study. Based on the literature review, the accuracy level achieved in this study is satisfactory for the analysis (Chen, 2003; Ismail and Jusoff, 2008). According to the review of literature, it should be noted that there is no standard rule set to specify the minimum level of accuracy required by local policymakers (which can be a good criterion for acceptance of the required accuracy range). Moreover, the city center is considered as the central place of growth of the city, which is in fact, the initial nucleus of formation of the city of Bandar Abbas located currently in the southwest of the city (the big market of the city). This center was identified by a circle of 452 km^2, which was inscribed in the city in a way that the contiguous urban pixels are fully inscribed. The inscribed circle is then partitioned into 32 equal sectors of 15 km^2 each, forming 32 different directions (North-Na1, Na2, Nb1, Nb2, Northeast-NEα1, NEα2, NEβ1, NEβ2, East-Eα1,Eα2, Eβ1, Eβ2, Southeast-SEα1, SEα2, SEβ1, SEβ2, South-Sα1, Sα2, Sβ1, Sβ2, Southwest-SWα1, SWα2, SWβ1, SWβ2,West-Wα1, Wα2, Wβ1, Wβ2 and Northwest-NWα1, NWα2, NWβ1, NWβ2) as shown in Fig. 3.

The drawn circles are concentric and include the entire scope of the study from the center of the city (nucleus of formation). Hence, the circles have been drawn in a way that they include the regions constructed based on the radius of 500 m from each other and at different geographic directions. This division has been made such that the process of changes in construction in different parts and direction could be statistically compared. It must be noted that the drawn circle has to be large enough to inscribe the totality of the urban boundary and constructed lands within it. Essentially, the structure of urban boundary is a dynamic process and greatly changes in different directions by the passing of time. However, in this study, the largest boundary is considered in the last period of time. Thus, the circle drawn is based on the last photo taken related to the GeoEye-1 satellite image of 2012.

As mentioned, the city of Bandar Abbas has been witnessing irregular changes during the past six decades in terms of space. Being a coastal city, the expansion has mainly been along the coastal line. The main limitations to the expansion of the city in recent years have been the existence of land for military uses (the Air Force and the international airport in the East, and the residential city of the Navy in the West) and the natural effects (the beach in the South and rocky cliffs in the North). The current boundary of Bandar Abbas includes 74 separate areas and three regions, each being under the supervision of a different municipality. The formation of the initial nucleus of the city is located in the South West. The neighborhoods of Suru, Nakhl Nakhoda, and Shaqo have villages around the city, which have joined the urban boundary over time due to the expansion of the urban boundary. It should be noted that the rate of expansion of the city in different parts has been different with the passage of time. This is the main reason why we divided the boundary under study into concentric circles and as opposed to using the conventional administrative boundaries. Nevertheless, the main discrepancy in using such a method is the fact that there is no administrative boundary-related data. Next, the built-up regions of the various zones and temporal instant (1956–2012) were extracted based on the classification of aerial photos and satellite images. In order to extract the built-up areas in aerial photos, the operation of the photogrammetry and outlining the features were used. For the satellite images, the built-up areas were extracted based on processing and classification operations. The extent of the built-up area was then calculated zone-wise. Table 2 illustrates the result of the computation. In Fig. 4, the overall process of doing the research methodology is briefly indicated.

2. Result and analysis

2.1. Urban extent

The results of classification and extraction of features have been obtained in 6 time spans using aerial photos and satellite images for the zones which experienced built-up and the zones which lack built-up. Fig. 4 shows the built-up and non-built-up zones (agriculture land, barren land, coastal zones, hole land, military land, river and rocky hills) in urban boundary and defined times. The study of the classified images indicates the existence of urban sprawls of different sizes and directions.

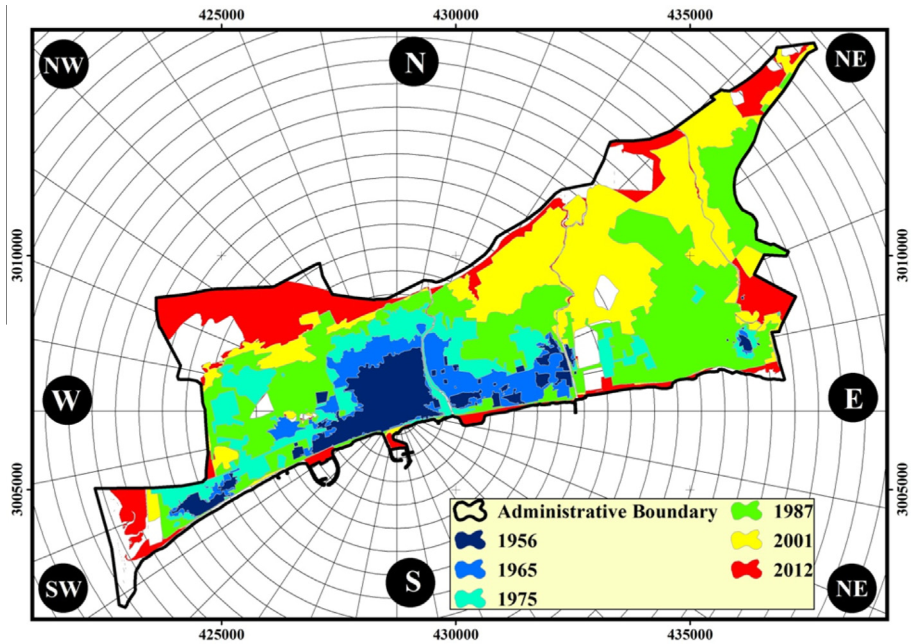

Figure 3 Overlay of classified images shows the urban expansion in different directions.

This means that while certain zones tend to be more compact, others are more openly spaced between built-up areas. Also, the boundaries between some built-up and non-built-up areas are completely clear, whereas these boundaries have merged with each other in other urban and non-urban classes. It was also found that variations in urban margins in each zone have occurred between time spans in different directions.

The presence of filled spaces between open spaces of the built-up areas, which are shown in Fig. 5, is fully clear. Based on the interpretation of the obtained images, it can be argued that the Bandar Abbas city is changing from a monocentric to a polycentric state. Certainly, the study of these patterns directly helps one to understand urban growth processes, but one needs strong evidence for discussion and decision to predict urban growth in the future. To elaborate intelligent differences between the patterns, it is vital to gain advanced understanding of how these zones change over a period using various quantitative criteria for measurement.

2.2. Built-up area and urban growth

The percentage of the region covered with impervious surfaces such as paved roads, urban sidewalks and concrete yards, which is effective on urban growth in direct measurements has been considered (Barnes et al., 2001). From this growth trend, the developed regions, which have a higher percentage of impervious surfaces than the less developed regions are considered in calculation (Sudhira et al., 2004). Table 2 shows the zone wise built-up regions per time span, which directly specifies the conditions of the built-up areas across the city. For better understanding, urban growth variation trend matrix is shown in Fig. 6A–F (the Radar Chart). In general, information about the variation trend of the built-up areas of Bandar Abbas city in different directions and times is shown in Table 2 and Fig. 6A–F. As mentioned earlier, the observed growth in the regions which built up within the time spans of 1956–1969, 1965–1975, 1975–1987, 1987–2001 and 2001–2012

Table 2 The built-up area (in hectares).

	1956	1965	1975	1987	2001	2012
Nα1	4.73	13.56	18.28	24.82	26.36	27.38
Nα2	3.84	14.89	19.69	30.47	30.46	30.63
Nβ1	5.86	14.92	20.85	35.43	35.61	35.63
Nβ2	5.39	15.58	24.25	38.41	39.37	40.83
NEα1	5.16	14.27	20.96	43.32	56.52	62.32
NEα2	5.85	12.35	29.55	37.03	60.07	147.00
NEβ1	6.28	10.16	16.69	118.71	212.24	313.22
NEβ2	5.97	12.19	32.45	142.01	235.64	364.78
Eα1	20.35	43.28	79.46	194.44	251.08	333.35
Eα2	19.50	30.81	47.48	112.32	150.88	223.83
Eβ1	4.00	4.12	6.83	6.95	8.53	8.63
Eβ2	1.60	1.72	1.81	1.99	1.65	1.62
SEα1	0.98	1.01	1.08	1.11	0.92	1.07
SEα2	0.73	0.86	0.91	1.00	0.77	0.79
SEβ1	0.46	0.58	0.58	0.68	0.82	0.83
SEβ2	0.78	0.78	0.78	0.83	0.71	0.71
Sα1	0.17	0.21	0.25	0.35	0.25	0.30
Sα2	0.40	0.51	0.58	0.66	0.57	0.58
Sβ1	0.43	0.52	0.54	0.55	0.68	0.74
Sβ2	0.63	0.77	0.84	0.96	0.74	0.78
SWα1	1.06	1.09	1.22	1.35	1.35	1.10
SWα2	1.87	1.95	1.99	2.22	1.90	1.89
SWβ1	2.94	3.18	3.22	3.89	3.11	3.08
SWβ2	33.38	41.14	56.53	78.97	88.99	94.40
Wα1	14.31	15.13	39.04	85.41	92.36	95.80
Wα2	8.03	11.14	34.18	72.29	80.56	78.88
Wβ1	9.94	17.08	41.74	91.34	95.38	89.90
Wβ2	7.93	12.11	15.63	67.62	73.21	77.12
NWα1	3.93	11.36	14.57	26.14	29.84	35.86
NWα2	4.36	17.89	20.51	33.94	39.42	40.49
NWβ1	4.67	15.04	19.77	35.26	39.85	39.45
NWβ2	4.03	12.99	18.01	23.88	29.06	29.48
The city	189.57	353.21	590.28	1314.37	1688.89	2182.48

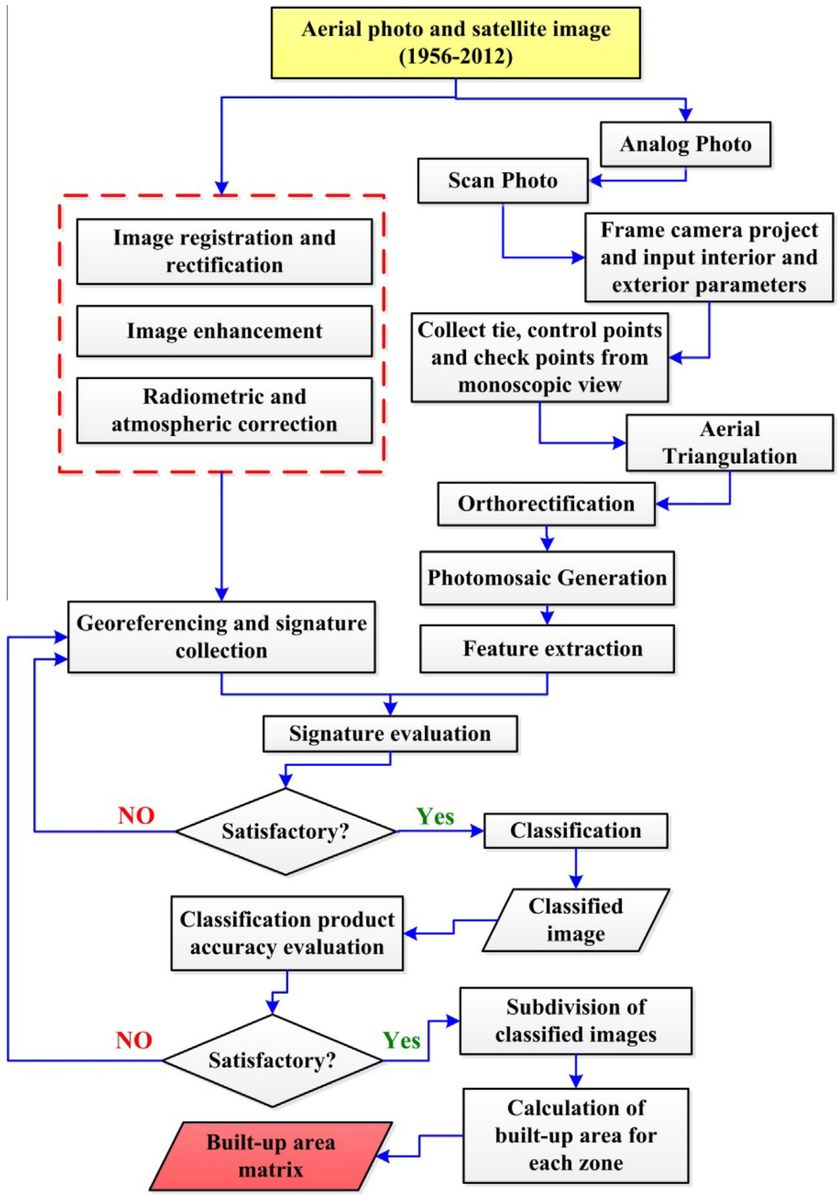

Figure 4 The Flowchart of image analysis.

were calculated (Table 3). The percentage of increase in the built-up regions is illustrated in Table 4, which also signifies the rate of urban growth. From the table, it can be clearly seen that the urban growth rate was decreasing gradually. In this study, unusual urban growth rate was observed during the past 6 decades from 28.77% (2001–2012) which is the minimum to 122.67% (1975–1987) which is the maximum. Although the available findings indicate a reduction of urban growth rate over time, it does not necessarily show any regular compression and suitable urban sprawl. Therefore, the need for further analysis is evident.

2.3. The difference between the observed and expected urban growth

In an attempt to outline the different properties of growth, the observed and the expected growth rates have to be ascertained and observed. Table 3 illustrates the observed growth of the usage of urban land. Here, the expected growth is computed using Eq. (1); where Table 3 is regarded as matrix M with elements M_{ij}, where $i = 1, 2, \ldots, n$ (the time span of the analysis, Table rows) and $j = 1, 2, \ldots, m$ (specific zone, Table columns). The expected growth of the built-up regions per variable is computed by multiplying the special time span of the analysis by the defined zone and dividing it by its total sum (Almeida et al., 2005):

$$M_{ij}^{E} = \frac{M_j^S \times M_j^S}{M_g} \quad (1)$$

where, M_i^S = row total

M_j^S = column total

$$M_g = \text{grand total} = \sum_{i=1}^{n}\sum_{j=1}^{m} M_{ij}$$

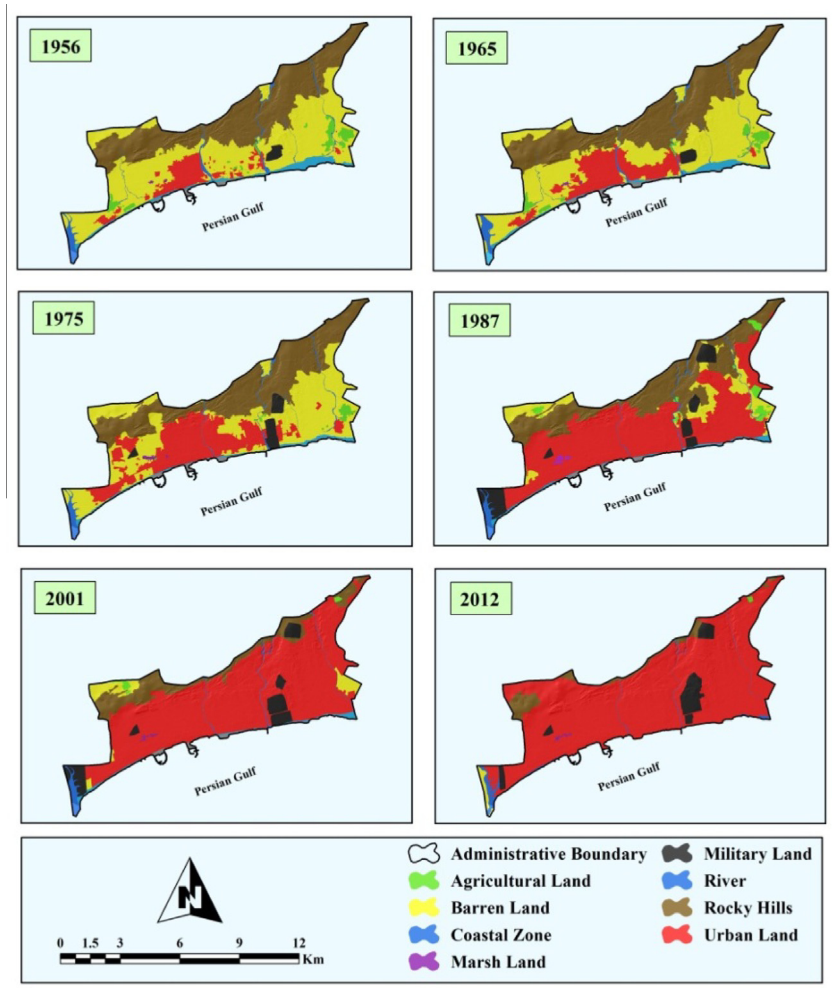

Figure 5 Classified images of six temporal instants showing built-up areas and non-built-up area.

The result obtained from calculations using Eq. (1), which gives the expected growth is illustrated in Table 5. By subtracting Table 3 (the observed built-up) from Table 4 (the expected built-up), Table 6 is created. Table 6 illustrates the difference between the urban growth per zone per time span. The negative results are indicative of a lower growth rate while the positive growth rate indicates urban growth. The degree of deviation is another parameter that has been studied in the current research. Here, it can be seen that the observed urban growth deviated significantly from the expected growth in certain areas. This marked deviation is indicative of the freedom of the variable. In the case of high deviation, it can be argued that the desired variable is independent of other similar groups of the variables. Nevertheless, only 5 time spans and one degree of freedom are found in the analysis. Increase of time spans in the analysis can help understand the behavior of the independent variables. Specifically, 5 time spans have been studied for analysis considering data availability in the defined time intervals. It is necessary to note that the results of the built-up expected zones have been based on the mentioned analysis and statistical method irrespective of urban planning and policies over time. It can be easily noted that the presence of suitable regions for the development of each zone is different from each other. Hence, urban planning and policymaking toward the expected urban growth of the city should be applied for promoting statistical analysis in the studied zones. The zones which have the lowest value of suitable lands for development clearly have the lowest expected growth. This method also takes into consideration the land available for development.

2.4. Pearson's chi-square statistics and urban growth

The Pearson's chi-square distribution employs the freedom between variable pairs to describe the change in land use within the same class (Almeida et al., 2005); using the relation $(Observed - Expected)^2/Expected$. This relation shows freedom or degree of deviation of the observed urban growth compared with the expected urban growth. The observed and the expected growth rates are displayed in Table 3 and Table 7, respectively. Here, the Chi-square statistical relation has been calculated for each time span of (X_i^2) based on Eq. (2) and its results are shown in Table 7:

$$X_i^2 = \sum_{j=1}^{m} \frac{\left(M_j - M_j^E\right)^2}{M_j^E} \quad (2)$$

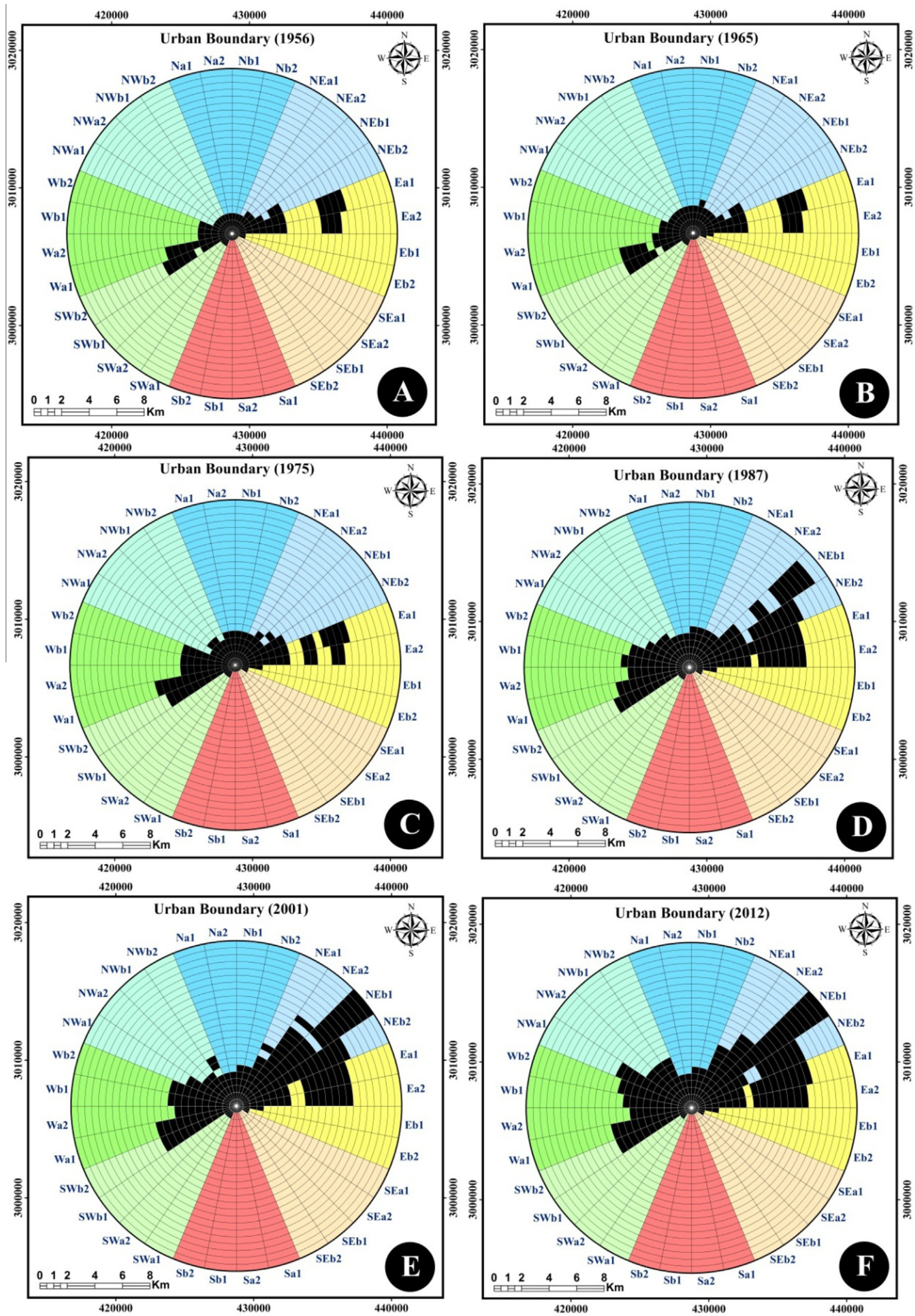

Figure 6 Radar chart showing the built-up area in the different directions.

where, X_i^2 is the degree-of-freedom for the i-th temporal span, while M_j is the observed built-up area in the j-th column for a specific row, M_j^E is the expected built-up area in the j-th column for a specific row. Hence, with a change in j (column) by i (row), and m (number of columns) by n (number of rows) in Eq. (2), the degree-of-freedom can be characterized per zone

Table 3 Observed growth in built-up area (in hectare).

	1956–1965	1965–1975	1975–1987	1987–2001	2001–2012	Row total
Nα1b	8.83	4.72	18.28	6.54	1.03	39.40
Nα2	11.06	4.80	19.69	10.78	0.17	46.49
Nβ1	9.07	5.93	20.85	14.58	0.02	50.44
Nβ2	10.19	8.66	24.25	14.16	1.47	58.73
NEα1	9.11	6.69	20.96	22.36	5.80	64.92
NEα2	6.50	17.20	29.55	7.48	86.92	147.65
NEβ1	3.88	6.53	16.69	102.02	100.98	230.11
NEβ2	6.22	20.26	32.45	109.56	129.14	297.63
Eα1	22.92	36.18	79.46	114.99	82.28	335.83
Eα2	11.31	16.67	47.48	64.84	72.95	213.25
Eβ1	0.12	2.72	6.83	0.12	0.09	9.88
Eβ2	0.12	0.09	1.81	0.18	0.17	2.37
SEα1	0.03	0.07	1.08	0.03	0.14	1.36
SEα2	0.13	0.05	0.91	0.09	0.01	1.19
SEβ1	0.13	0.00	0.58	0.10	0.01	0.82
SEβ2	0.00	0.00	0.78	0.06	0.00	0.83
Sα1	0.04	0.04	0.25	0.10	0.05	0.49
Sα2	0.11	0.06	0.58	0.08	0.01	0.84
Sβ1	0.09	0.02	0.54	0.02	0.06	0.71
Sβ2	0.14	0.07	0.84	0.12	0.04	1.22
SWα1	0.03	0.12	1.22	0.14	0.15	1.66
SWα2	0.08	0.04	1.99	0.22	0.09	2.43
SWβ1	0.24	0.04	3.22	0.67	0.07	4.23
SWβ2	7.76	15.40	56.53	22.44	5.42	107.54
Wα1	0.81	23.91	39.04	46.37	3.44	113.58
Wα2	3.10	23.05	34.18	38.10	1.33	99.76
Wβ1	7.14	24.66	41.74	49.61	1.52	124.66
Wβ2	4.18	3.52	15.63	51.99	3.91	79.23
NWα1	7.43	3.20	14.57	11.57	6.03	42.80
NWα2	13.53	2.62	20.51	13.43	1.07	51.16
NWβ1	10.38	4.72	19.77	15.50	0.61	50.97
NWβ2	8.97	5.02	18.01	5.86	0.42	38.29
Column total	163.64	237.08	590.28	724.08	505.40	2220.48

(X_i^2) (Table 8). In this way, the aggregate degree-of-freedom is computed as shown in Eq. (3) (Table 13):

$$X^2 = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{\left(M_{ij} - M_{ij}^{E}\right)^2}{M_{ij}^{E}} \tag{3}$$

When the limit of the chi-square i is below 0, the observed value is exactly equal to the expected value. Table 7 clearly shows that there is a very high degree-of-freedom for all 5 time spans (difference between the observed and expected values). Table 8 indicates a low degree-of-freedom (for both observed and expected values) including the development directions of Eβ2, SEα1, SEα2, SEβ1, SEβ2, Sα1, Sα2, S1, Sβ2, SWα1, SWα2 and SWβ1 while the development directions of Nα1, Nα2, Nβ1, Nβ2, NEα1, NEα2, NEβ1, NEβ2, Eα1, Eα2, Eβ1, SWβ2, Wα1, Wα2, Wβ1, Wβ2, NWα1, NWα2, NWβ1 and NWβ2 are very high. Based on the obtained results, a very high sum of degree-of-freedom is attained (Table 13).

The sum of degrees-of-freedom shows lack of equal balance and dissimilarity in urban policies and planning considered in the past 6 decades. High degree-of-freedom in a zone indicates unsustainable development in the desired zone over time and high degree of freedom for a defined time span indicates diversity and variability of urban growth in high scale. However, it is necessary to note that high degree of freedom cannot be regarded as urban sprawl and instead, the difference between the growth pattern and process should be considered. This analysis method based on long time spans is regarded as a new methodology and thus, depicts a new contribution to the body of knowledge in the research direction.

The Chi-square model has been used for determining the sum of degree of freedom by Bonham-Carter (1994), Almeida et al. (2005) and Bhatta et al. (2010). But this research has studied the models which have been used for urban analysis (using aerial photos and satellite images) in different dimensions such as pattern, process and total sum.

2.5. Shannon's entropy and urban growth

Shannon's entropy is regarded as one of the employed methods of pattern determination and process of the sprawl formation of cities over time (Kumar et al., 2007; Lata et al., 2001; Li and Yeh, 2004; Sudhira et al., 2004; Yeh and Li, 2001).

In the current investigation, the Shannon's entropy statistical model has been calculated using Eq. (4) and information inserted in Table 4 for each time span (H_i):

$$H_i = -\sum_{j=1}^{m} p_j \log_e(p_j) \tag{4}$$

where p_j is the variable's proportion in the j-th column (i.e. the proportion of built-up growth rate in the j-th zone, computed

Table 4 Built-up growth rate of fifty-six-yearly periods (in percent).

	1956–1965	1965–1975	1975–1987	1987–2001	2001–2012
Nα1	186.50	34.80	35.79	6.18	3.90
Nα2	288.16	32.24	54.72	−0.03	0.54
Nβ1	154.74	39.71	69.92	0.52	0.05
Nβ2	189.22	55.60	58.40	2.50	3.72
NEα1	176.64	46.87	106.68	30.48	10.26
NEα2	111.01	139.34	25.31	62.23	144.69
NEβ1	61.83	64.27	611.12	78.78	47.58
NEβ2	104.21	166.26	337.63	65.93	54.80
Eα1	112.64	83.60	144.71	29.12	32.77
Eα2	57.98	54.10	136.56	34.33	48.35
Eβ1	2.94	65.96	1.69	22.80	1.11
Eβ2	7.71	5.16	9.76	−16.99	10.52
SEα1	3.08	6.95	2.65	−16.99	15.71
SEα2	18.35	5.53	9.57	−22.50	1.64
SEβ1	27.53	0.00	17.25	20.06	1.08
SEβ2	0.00	0.00	7.36	−14.78	0.00
Sα1	24.52	20.24	40.51	−28.70	19.86
Sα2	27.58	12.37	14.26	−13.88	1.22
Sβ1	20.41	3.39	2.82	23.30	8.57
Sβ2	21.80	9.48	14.41	−23.27	5.87
SWα1	2.67	11.38	11.31	−0.45	11.24
SWα2	4.47	2.25	11.12	−14.40	4.70
SWβ1	7.99	1.21	20.85	−19.92	2.13
SWβ2	23.24	37.42	39.70	12.68	6.09
Wα1	5.69	158.10	118.78	8.14	3.73
Wα2	38.66	206.96	111.46	11.44	1.65
Wβ1	71.77	144.38	118.85	4.41	1.59
Wβ2	52.78	29.06	332.53	8.27	5.34
NWα1	188.83	28.20	79.44	14.13	20.20
NWα2	310.13	14.64	65.47	16.16	2.73
NWβ1	222.41	31.41	78.42	12.99	1.53
NWβ2	222.72	38.64	32.54	21.70	1.45
The city	86.32	67.12	122.67	28.49	29.92

from Table 4 using the built-up growth rate in j-th zone/the aggregated built-up growth rates across the zones). Here, m denotes the summation of zones, which is 32 in the current study. The degree-of-sprawl in this case, is derived from the entropy value, which falls within the limit $0 \leqslant x \leqslant \log_e(m)$. At 0, the built-up distribution is said to be compact, while sparse distribution increases with increasing divergence from zero.

Table 9 illustrates that the attained entropy from the study is greater than half of the index $\log_e(m)$. As such, one can conclude that the Bandar Abbas city underwent a sprawl during the past 6 decades. However, urban sprawl has been reduced over time. Based on the research findings by Richardson et al. (2000), towns and cities in developing countries are being compressed considering the structure of their formation based on decentralization and there is evidence that the general trend of the developing countries is being more compressed. Based on the studies conducted by Iranian Ministry of Road and Urban Development, it is shown that most cities of the countries are experiencing increasing sprawl trend. According to the performance analysis, it can be argued that the Bandar Abbas city has limited chances of sprawl considering the trend during the past periods due to limitations in development in the various geographical directions; depicting a descending trend over time. These findings also show that administrative boundaries cannot give the real understanding of urban growth. The result further indicates that the Bandar Abbas city has high sprawl. However, where the entropy value is below half of $\log_e(m)$, it can be argued that the city has no chance of sprawl. Eq. (5), which is the revised form of Eq. (4) is used for determining the entropy of each zone:

$$H_j = -\sum_{i=1}^{n} p_i \log_e(p_i) \tag{5}$$

where p_i is the proportion of the variable in the i-th row (i.e. proportion of built-up growth rate in i-th temporal span, computed from Table 4 using the built-up growth rate in the i-th temporal span/the aggregated built-up growth rate across the time spans). Here, n is the total number of temporal spans, which is 5 in the current study.

Table 10 illustrates that more than half of $\log_e(m)$ entropy values are achieved, implying that the zones are being sprawled. Based on the performed analysis, it can be argued that the Bandar Abbas city had a general sprawl in all the geographical directions, particularly in the eastern and northern zones of the city. For this reason, it had lower sprawl in the western direction, and particularly the southern direction based on the limitations of the seashore and the military zone of the marine force. The total aggregated sprawl can be determined using the relation:

Table 5 Expected growth of built-up area (in hectare).

	1956–1965	1965–1975	1975–1987	1987–2001	2001–2012
Nα1	1.85	2.67	8.17	4.26	0.26
Nα2	2.18	3.16	9.66	5.04	0.04
Nβ1	2.43	3.51	10.73	5.60	0.00
Nβ2	2.89	4.18	12.78	6.67	0.37
NEα1	4.66	6.75	20.61	10.76	1.46
NEα2	11.50	16.66	50.88	26.57	21.88
NEβ1	25.01	36.23	110.65	57.78	25.42
NEβ2	29.23	42.35	129.36	67.54	32.51
Eα1	25.50	36.95	112.84	58.92	20.71
Eα2	16.65	24.12	73.66	38.46	18.37
Eβ1	0.38	0.55	1.67	0.87	0.02
Eβ2	0.10	0.14	0.44	0.23	0.04
SEα1	0.02	0.03	0.08	0.04	0.01
SEα2	0.04	0.05	0.16	0.09	0.01
SEβ1	0.03	0.04	0.13	0.07	0.00
SEβ2	0.01	0.02	0.05	0.03	0.01
Sα1	0.02	0.03	0.09	0.05	0.01
Sα2	0.02	0.03	0.10	0.05	0.00
Sβ1	0.03	0.04	0.11	0.06	0.01
Sβ2	0.04	0.05	0.17	0.09	0.02
SWα1	0.04	0.05	0.16	0.08	0.03
SWα2	0.07	0.10	0.30	0.15	0.10
SWβ1	0.09	0.12	0.38	0.20	0.01
SWβ2	4.97	7.20	22.00	11.49	1.36
Wα1	6.64	9.62	29.38	15.34	0.87
Wα2	6.02	8.72	26.62	13.90	0.33
Wβ1	7.08	10.26	31.35	16.37	0.38
Wβ2	5.64	8.17	24.94	13.02	0.98
NWα1	2.60	3.77	11.51	6.01	1.52
NWα2	2.94	4.26	13.03	6.80	0.27
NWβ1	2.92	4.22	12.90	6.74	0.15
NWβ2	2.07	3.00	9.18	4.79	0.11

$$H = -\sum_{i=1}^{n}\sum_{j=1}^{m} p_{ij}\log_e(p_{ij}) \tag{6}$$

where p_{ij} is the proportion of the i-th row variable and j-th column (i.e. the proportion of the built-up growth rate in the i-th temporal span and the j-th zone, generated from Table 4 by using the built-up growth rate in the i-th temporal span and j-th zone/the aggregate of all variables). In the study, the upper limit of the aggregated sprawl is calculated using $\log_e(n \times m)$, which was found to be 5.76. By using Eq. (6), the final overall sprawl was found to be 4.53, which is much greater than half of $\log_e(n \times m)$ (i.e. 2.88). Based on this, it can be deduced that Bandar Abas has high overall sprawl, both in terms of the process and pattern during the period being studied (i.e. 1956–2010).

This section of the study focuses on the application of the entropy model in the current study using three different dimensions of urban growth, which is a new method of evaluating the urban sprawl pattern (Bhatta, 2009a, 2010; Kumar et al., 2007; Lata et al., 2001; Li and Yeh, 2004; Sudhira et al., 2004; Yeh and Li, 2001).

2.6. Degree-of-goodness

The Chi-square model for the calculation of the degree-of-freedom and the Shannon entropy model for computing the degree-of-sprawl have different measurements, which may in fact, contradict each other in some cases (as evident in the current study). Thus, it is also vital to determine the degree-of-goodness for urban growth. The degree-of-goodness determines the observed growth, which relates to the expected growth and compression in urban regions (unlike sprawl). For this reason, the desired calculation method for each time span is given by Eq. (7), and the result is shown in Table 11:

$$G_i = \log_e\left[\frac{1}{X_i^2\left(\frac{H_i}{\log_e(m)}\right)}\right] \tag{7}$$

where G_i is the degree-of-goodness for the i-th temporal span, while X_i^2 is the degree-of-freedom for the i-th temporal span, H_i is the entropy for the i-th temporal span, m is the total number of zones, which is 32 in the current case. The degree-of-goodness for each zone is given in (Table 12), where i is interchanged with j, and m with n in Eq. (7). The aggregated degree-of-goodness is calculated thus in Eq. (8):

$$G = \log_e\left[\frac{1}{X^2\left(\frac{H}{\log_e(m \times n)}\right)}\right] \tag{8}$$

where, X^2 denotes the aggregated freedom and H, *the* overall sprawl (Table 13).

The degree-of-goodness can be regarded as a direct and straightforward measurement method. For this measurement, positive values are indicative of goodness while negative ones

Table 6 Difference between observed and expected built-up growth (in hectare).

	1956–1965	1965–1975	1975–1987	1987–2001	2001–2012
Nα1	6.98	2.05	−1.62	−2.73	0.77
Nα2	8.87	1.64	1.12	−5.03	0.11
Nβ1	6.64	2.41	3.85	−5.42	0.01
Nβ2	7.31	4.48	1.38	−5.71	1.10
NEα1	4.46	−0.06	1.75	2.44	4.34
NEα2	−5.00	0.54	−43.40	−3.52	65.04
NEβ1	−21.12	−29.70	−8.64	35.75	75.56
NEβ2	−23.01	−22.09	−19.80	26.09	96.63
Eα1	−2.58	−0.76	2.15	−2.29	61.57
Eα2	−5.34	−7.45	−8.82	0.09	54.59
Eβ1	−0.26	2.17	−1.55	0.71	0.07
Eβ2	0.02	−0.06	−0.26	0.43	0.13
SEα1	0.01	0.04	−0.05	0.02	0.03
SEα2	0.10	−0.01	−0.08	0.04	0.04
SEβ1	0.10	−0.04	−0.03	0.07	0.01
SEβ2	−0.01	−0.02	0.01	0.02	0.03
Sα1	0.02	0.01	0.01	−0.01	0.02
Sα2	0.09	0.03	−0.02	−0.04	0.01
Sβ1	0.06	−0.02	−0.10	0.07	0.04
Sβ2	0.10	0.02	−0.05	−0.05	0.07
SWα1	−0.01	0.07	−0.02	−0.07	0.10
SWα2	0.02	−0.05	−0.07	−0.06	0.28
SWβ1	0.15	−0.08	0.29	−0.13	0.03
SWβ2	2.79	8.19	0.44	−1.47	4.05
Wα1	−5.82	14.30	16.99	−8.39	2.57
Wα2	−2.91	14.33	11.48	−5.63	0.99
Wβ1	0.05	14.40	18.26	−12.34	1.14
Wβ2	−1.45	−4.65	27.04	−7.43	2.92
NWα1	4.83	−0.56	0.06	−2.32	4.51
NWα2	10.58	−1.65	0.40	−1.32	0.80
NWβ1	7.46	0.50	2.60	−2.16	0.46
NWβ2	6.89	2.02	−3.31	0.39	0.31

Table 7 Degree-of-freedom for urban growth in each temporal span.

Time span	Freedom (X_i^2)
1956–1965	242.83
1965–1975	135.17
1975–1987	102.45
1987–2001	74.49
2001–2012	1124.54

are indicative of badness. This goodness or badness can be determined from the information in Tables 11–13. Here, the variables of degree-of-goodness can be positive or negative good depending on the zone and time span. From the result, it can be argued that urban boundaries had no good experience of urban growth trend in the time span of 1956–2012. Separate analysis of each zone out of the desired zones also shows similar results. Although southeastern, southern and southwestern zones have positive values, high positive values are found only in zones Sα1 and SEβ2. As Table 13 shows, the overall goodness depicts a worse condition.

3. Discussion

It could be recalled that the current study has been conducted in 5 time spans using aerial photos and satellite images for a 56-year time interval. Certainly, better results will be obtained if more images were studied and analyzed in shorter time spans. Also, the reliability of the statistical analysis will improve by increasing the number of variables. Based on the mentioned research method, the studied zone was divided into 32 equal parts in different geographical directions to determine urban sprawl trend. In addition, the studied zone was further divided into concentric circles, for better results and understanding of urban growth trend in Bandar Abbas from the past to the present. In different zones, there are different levels of compression and this factor causes varying urban growth patterns. As such, a unique policy designed for a city cannot be suitably applied for other cities with equal effectiveness.

As mentioned earlier, the main goal of this study is to investigate new analysis methods based on 5 time spans and 32 geographical directions in urban growth trend instead of urban comprehensive studies. It is necessary to note that if a city is divided into circular zones and sections based on geographical directions, distance to commercial zones will be directly considered in a definite zone and this may be very useful in trend analysis. It is very important to specify the distance to centers of commercial zones for determining changes of urban density. It is also necessary to note that the center of the circle and the desired zones have been considered based on the primary goal of the city formation. In this study, it is assumed that there is an equal possibility of growth in all directions of the city center

Table 8 Degree-of-freedom for urban growth in each zone.

Zone	Freedom (X_i^2)
Nα1	32.34
Nα2	42.39
Nβ1	26.49
Nβ2	31.59
NEα1	17.86
NEα2	233.01
NEβ1	289.58
NEβ2	329.96
Eα1	183.40
Eα2	167.32
Eβ1	11.04
Eβ2	1.38
SEα1	0.21
SEα2	0.44
SEβ1	0.44
SEβ2	0.13
Sα1	0.10
Sα2	0.44
Sβ1	0.47
Sβ2	0.52
SWα1	0.46
SWα2	0.92
SWβ1	0.72
SWβ2	23.12
Wα1	48.43
Wα2	35.15
Wβ1	43.50
Wβ2	45.26
NWα1	23.35
NWα2	41.35
NWβ1	21.71
NWβ2	26.44

Table 9 Shannon's entropy of each temporal span.

Time span	Entropy (H_i)	$\log_e(m)$	$\log_e(m)/2$
1956–1965	2.923	3.58	1.79
1965–1975	2.912	3.58	1.79
1975–1987	2.761	3.58	1.79
1987–2001	2.966	3.58	1.79
2001–2012	2.491	3.58	1.79

and that no commercial center, special lands, road network and other variables have unequal growth. However, it is not necessary to consider urban boundary based on a circular zone. Instead, natural boundaries or urban boundaries can be used and divided it into different sections. Administrative boundaries can also be considered (although they do not reflect dynamicity of urban sprawl), which in fact, reflects economic and social dependencies and independencies. Natural boundaries are seldom affected by data of social and economic variables. In many countries such as Iran, data relating to socioeconomic variables which relate to administrative boundaries are accessible. For this reason, the city was divided into 24 parts for analyzing urban growth pattern using social-economic variables and Shannon's entropy model considering the administrative boundary of Bandar Abbas. The models shown in the present study are not directly dependent on the

Table 10 Shannon's entropy for different zones.

Zone	Entropy (H_i)	$\log_e(m)$	$\log_e(m)/2$
Nα1	0.93	1.61	0.80
Nα2	0.70	1.61	0.80
Nβ1	0.96	1.61	0.80
Nβ2	1.02	1.61	0.80
NEα1	1.28	1.61	0.80
NEα2	1.48	1.61	0.80
NEβ1	1.00	1.61	0.80
NEβ2	1.38	1.61	0.80
Eα1	1.44	1.61	0.80
Eα2	1.48	1.61	0.80
Eβ1	0.83	1.61	0.80
Eβ2	1.33	1.61	0.80
SEα1	1.54	1.61	0.80
SEα2	1.50	1.61	0.80
SEβ1	1.14	1.61	0.80
SEβ2	1.08	1.61	0.80
Sα1	1.46	1.61	0.80
Sα2	1.19	1.61	0.80
Sβ1	1.33	1.61	0.80
Sβ2	1.48	1.61	0.80
SWα1	1.38	1.61	0.80
SWα2	1.38	1.61	0.80
SWβ1	1.01	1.61	0.80
SWβ2	1.44	1.61	0.80
Wα1	0.93	1.61	0.80
Wα2	1.05	1.61	0.80
Wβ1	1.14	1.61	0.80
Wβ2	0.77	1.61	0.80
NWα1	1.18	1.61	0.80
NWα2	0.78	1.61	0.80
NWβ1	0.99	1.61	0.80
NWβ2	0.95	1.61	0.80

Table 11 Degree-of-goodness for urban growth in each temporal span.

Time span	Goodness (G_i)
1956–1965	−6.015
1965–1975	−5.426
1975–1987	−5.095
1987–2001	−4.848
2001–2012	−7.388

selection of the studied zone and its divisions. They are also not dependent on the number of divisions. Of course, it is necessary to note that the more the number of divisions, the more accurate the result. The performed measurements of the study are based on the per zone built-up regions. Anyway, the regions which have accessible lands for development are not equal in each zone. Therefore, it is better to calculate three measurement methods of freedom, sprawl, and goodness based on percentage of the built-up areas in each zone. This percentage can be calculated using Eq. (9):

$$\frac{(\text{Built-up area within a zone})}{(\text{total area of the zone} \times \text{non-development land within the zone})} \times 100 \quad (9)$$

Table 12 Degree-of-goodness for urban growth in each zone.

Zone	Goodness (G_i)
Nα1	−2.93
Nα2	−2.92
Nβ1	−2.76
Nβ2	−2.99
NEα1	−2.65
NEα2	−5.36
NEβ1	−5.20
NEβ2	−5.65
Eα1	−5.10
Eα2	−5.04
Eβ1	−1.73
Eβ2	−0.13
SEα1	1.62
SEα2	0.90
SEβ1	1.17
SEβ2	2.42
Sα1	2.45
Sα2	1.12
Sβ1	0.96
Sβ2	0.74
SWα1	0.94
SWα2	0.24
SWβ1	0.80
SWβ2	−3.03
Wα1	−3.33
Wα2	−3.14
Wβ1	−3.43
Wβ2	−3.07
NWα1	−2.84
NWα2	−3.00
NWβ1	−2.59
NWβ2	−2.74

Table 13 Overall degree-of-freedom, entropy, and degree-of-goodness.

Degree-of-freedom (X^2)	Entropy (H)	Degree-of-goodness (G)
1679.483	4.530	−7.313

It is necessary to note that the area of the developed lands cannot be directly measured with aerial photos and satellite images. Different factors may play a role in non-sprawl of a region, which include natural factors (rivers, coasts and rough lands), ownership (land ownership by military forces), policies of government (for protecting open spaces, aquatic, agricultural and green spaces), legal disputes on lands, etc. Therefore, it may be hard to collect this dataset in different time spans. However, if these data are accessible, the percentage of the non-built areas in the desired zones will attain more accuracy.

The method used in the current study may be criticized as a result of its simplicity in the analysis of urban growth. The reasons which can be effective are failure to use road network, distribution of commercial centers in urban boundary, special lands, change of land uses over time and many other cases which are mentioned in the introduction of the paper and have been studied and analyzed by researchers. It should be noted that many of the cities in the developing countries have been sprawled without sprawl plan over time. In most scenarios, these cities do not have any historical data of urban sprawl or related land use data over a period of time. As such, the majority of the spatio-statistical models are not suitable for studying urban growth patterns. In addition, many of the urban managers (for example: Bandar Abbas) do not have enough ability and proficiency to use the models, tools and new technologies such as geographic information system and remote sensing. Therefore, it is necessary to note that urban growth pattern should be determined based on simple analysis methods and the minimum input data should be employed. For this reason, one can study and analyze urban growth trend in the past and at present using the required minimum input data and aerial photos and satellite images based on the methods used and proposed in this study.

In this study, the proposed method determines the degree of goodness, however, one of the main limitations of the method is inability to apply and calculate the past political variables. Although there may be planned policies for the development of cities in industrial countries, the developing cities lack such policies in most cases and growth trend is completely free. Therefore, methods and approaches used in this study could be useful and applicable to numerous cities across the developing countries. This, however, does not imply that the models presented cannot be used for determining degree of goodness in cities of the industrialized countries. Because there are no predetermined growth policy and planning for Bandar Abbas, the expected urban growth has been calculated using statistical methods and based on urban growth trend in the past and present (Eq. (1)). In many cities of the industrial countries, the expected urban growth has been predetermined and planned for the future. Therefore, the predetermined values should be considered considering the variables available in Eq. (1) for such cities. As a result, the quantity of degree-of-freedom and degree-of-goodness will be influenced by these variables. Even though the primary goal of this study is to investigate new methods and models, the results obtained have analyzed urban growth pattern in Bandar Abbas. The information obtained from the research models can be used in the future by local planners and managers in understanding sprawling trend of the urban boundary in the past and present for preparing development projects. In fact, understanding urban growth complexity allows one to be familiar with some necessary tools which have been introduced in recent years with efficient, stable and realistic principles.

Finally, the degree-of-goodness shows sustainable development can be discussed and judged in terms of sustainability measurement methods based on experimental evidence. Since the degree-of-goodness is based on two observed and expected variables calculated, this method is introduced as a direct measurement of urban growth. Certainly, most analyses can show correlation between degree-of-goodness and sustainable urban growth. However, in-depth analysis of sustainable development is not within the scope of the current study. In fact, sustainable development is known as a multilateral process and considers development of all aspects which are effective in the life of humans and creatures (Hasna, 2007). This means that it settles conflicts between different competitive goals which include concurrent priorities of environmental quality, economic welfare and social justice. For this reason, the trend is a continual process. Urban growth is very important for achieving sustainable development, and requires the observance of all planned principles and performance of the predetermined policies (by governments in future). However, the trend of achieving sustainable development is not naturally a fixed process. Instead, it is a multidimensional set which is based on the interaction between the characteristics and specifications of systems in future. It can, therefore, be argued that the degree-of-goodness models do not have the capacity to determine the sustainable development directly. Instead, it is likely that the degree-of-goodness model can be converted into one of the determined indices of sustainable development. However, it will be better to create correlation between the two for determining the reliability before such conclusion.

4. Conclusions

The goal of the current study is to investigate the urban growth of the Iranian city of Bandar Abbas using the retrieved data spanning 6 decades using aerial photos and satellite images and new statistical methods. In the study, various statistical models were employed for studying and analyzing urban growth based on aspects of the pattern including general processes and conditions. The models showed that the city exhibits high degree of freedom and sprawl. Moreover, the urban sprawl trend was found to reduce over time while the degree of freedom trend was found to increase. Specifically, the degree-of-goodness was found to be improper, with a warning condition. Also, the goodness of the urban growth showed a descending trend despite the reduction of urban growth rate. The result further showed that the proposed models can be useful tools for identifying urban growth patterns and their general tendencies. The models, which have been used for analyzing urban growth based on specified measurement scales and variables of the observed built zones and expected built zones, include the Person's chi-square, Shannon's entropy and degree-of-goodness. The models shown in the study have been devised experimentally and not presented by the strong theories which are limited to a special zone. Therefore, they can be easily applied in other cities which have spatial and attribute data from the past and present, particularly the developing countries. As such, the new hypothesis, which can be put forward based on the analysis in the study, is that the degree-of-goodness model can be regarded as a sustainable development index and constitutes a vital tool to future researchers.

The current study also focused on a special scope of the research, which is the application of the shown models for determining and identifying urban growth trend of the Bandar Abbas city, which can be used by urban planners and managers. The scope of the study is limited to the application of the referred models for urban planners and other users in developing countries; thanks to the motivation from the urban growth analysis theories and models developed by other researchers.

References

Al-Awadhi, T., 2007. Monitoring and modeling urban expansion using GIS and RS: Case study from Muscat, Oman. In: Proceedings of Urban Remote Sensing Joint Event. 11–13 April, 2007, Paris, France.

Alberti, M., 2005. The effects of urban patterns on ecosystem function. Int. Reg. Sci. Rev. 28 (2), 168–192.

Almeida, C.M., Monteiro, A.M.V., Mara, G., Soares-Filho, B.S., Cerqueira, G.C., Pennachin, C.S.L., 2005. GIS and remote sensing as tools for the simulation of urban land-use change. Int. J. Remote Sens. 26 (4), 759–774.

Angel, S., Sheppard, S.C., Civco, D.L., 2005. The dynamics of Global Urban Expansion. Available from. Washington D.C.: Transport and Urban Development Department, The World Bank. <http://www.citiesalliance.org/doc/resources/upgrading/urban-expansion/worldbank reportsept2005.pdf p. 200/>.

Belal, A.A., Moghanm, F.S., 2011. Detecting urban growth using remote sensing and GIS techniques in Al Gharbiya governorate. Egypt. J. Remote Sens. Space Sci. 14, 73–79.

Barnes, K.B., Morgan, J.M., III, Roberge, M.C., Lowe, S., 2001. Sprawl Development: Its Patterns, Consequences, and Measurement. A White Paper. Available from: Towson University <http://chesapeake.towson.edu/landscape/urbansprawl/download/Sprawl_white_paper.pdf/> (accessed 10.01.07).

Batisani, N., Yarnal, B., 2009. Urban expansion in centre county, Pennsylvania: spatial dynamics and landscape transformations. Appl. Geogr. 29 (2), 235–249.

Batty, M., Howes, D., 2001. Predicting temporal patterns in urban development from remote imagery. In: Donnay, J.P., Barnsley, M.J., Longley, P.A. (Eds.), Remote Sensing and Urban Analysis. Taylor & Francis, London, pp. 185–204.

Batty, M., Xie, Y., 1997. Possible urban automata. Environ. Plann. B 24, 175–192.

Belkina, T.D., 2007. Diagnosing urban development by an indicator system. Stud. Russ. Econ. Dev. 18 (2), 162–170.

Benati, S., 1997. A cellular automaton for the simulation of competitive location. Environ. Plann. B. 24, 205–218.

Bhatta, B., 2009a. Analysis of urban growth pattern using remote sensing and GIS: a case study of Kolkata, India. Int. J. Remote Sens. http://dx.doi.org/10.1080/01431160802651967.

Bhatta, B., 2009c. Modelling of urban growth boundary using geoinformatics. Int. J. Digit. Earth. http://dx.doi.org/10.1080/17538940902971383.

Bhatta, B., 2010. Analysis of Urban Growth and Sprawl from Remote Sensing Data. Springer-Verlag, Berlin, Heidelberg.

Bhatta, B., Saraswati, S., Bandyopadhyay, D., 2010. Quantifying the degree-of-freedom, degree-of-sprawl, and degree-of-goodness of urban growth from remote sensing data. Appl. Geogr. 30 (1), 96–111.

Bonham-Carter, G.F., 1994. Geographic Information Systems for Geoscientists: Modelling with GIS. Pergamon, Ontario, p. 398.

Chen, C., 2003. Frontiers of Remote Sensing Information Processing. World Scientific, p. 614.

Cho, S., Lambert, D.M., Roberts, R.K., Kim, S.G., 2010. Moderating urban sprawl: is there a balance between shared open space and housing parcel size? J. Econ. Geogr. 10 (5), 763–783.

Clark, D., 1982. Urban Geography: An Introductory Guide. Taylor & Francis, p. 231.

Clark, W.A., Hosking, P.L., 1986. Statistical Methods for Geographers. John Wiley and Sons, New York, 518 pp.

Clarke, K.C., Hoppen, S., Gaydos, L., 1997. A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. Environ. Plann. B. 24, 247–261.

Deadman, P.D., Brown, R.D., Gimblett, H.R., 1993. Modelling rural residential settlement patterns with cellular automata. J. Environ. Manage. 37, 147–160.

Deep, S., Saklani, A., 2014. Urban sprawl modeling using cellular automata. Egypt. J. Remote Sens. Space Sci. 17, 179–187.

Deng, J., Wang, K., Hong, Y., Jia, G., 2009. Spatio-temporal dynamics and evolution of land use change and landscape pattern in response to rapid urbanization. Landscape Urban Plann. 92, 187–198.

Dewan, A.M., Yamaguchi, Y., 2009. Land use and land cover change in Greater Dhaka, Bangladesh: using remote sensing to promote sustainable urbanization. Appl. Geogr. 29, 390–401.

Donnay, J.P., Barnsley, M.J., Longley, P.A., 2001. Remote sensing and urban analysis. In: Donnay, J.P., Barnsley, M.J., Longley, P.A. (Eds.), Remote Sensing and Urban Analysis. Taylor and Francis, London and New York, pp. 3–18.

Farhoudi, R., Zanganeh, S.S., Saed Moucheshi, R., 2009. Spatial distribution of population in Iranian urban system. Q. Geogr. Res. 68, 55–68.

Fotheringham, A.S., Wegener, M., 2000. Spatial Models and GIS: New Potential and New Models. Taylor and Francis, London, p. 279.

Galster, G., Hanson, R., Wolman, H., Coleman, S., Freihage, J., 2001. Wrestling sprawl to the ground: defining and measuring an elusive concept. House Policy Debate 12 (4), 681–717.

Griffith, D.A., 1988. Advanced Spatial Statistics: Special Topics in the Exploration of Quantitative Spatial Data Series. Kluwer, Dordrecht.

Hasna, A.M., 2007. Dimensions of sustainability. J. Eng. Sustainable Dev. Energy Environ. Health 2 (1), 47–57.

Hedblom, M., Soderstrom, B., 2008. Woodlands across Swedish urban gradients: status, structure and management implications. Landscape Urban Plann. 84, 62–73.

Herold, M., Clarke, K.C., Scepan, J., 2002. Remote sensing and landscape metrics to describe structures and changes in urban land use. Environ. Plann. A. 34 (8), 1443–1458.

Herold, M., Goldstein, N.C., Clarke, K.C., 2003. The spatiotemporal form of urban growth: measurement, analysis and modeling. Remote Sens. Environ. 86, 286–302.

Herold, M., Hemphill, J., Dietzel, C., Clarke, K.C., 2005. Remote sensing derived mapping to support urban growth theory. Tempe, AZ, USA, March 14–16, 2005. Available from: Proceedings of the ISPRS joint conference 3rd International Symposium Remote Sensing and Data Fusion Over Urban Areas, and 5th International Symposium Remote Sensing of Urban Areas (URS 2005). <www.isprs.org/commission8/workshop_urban/herold_hemphill_etal.pdf/>.

Iranian Statistic Center (2012). Census data. Tehran, Iran.

Iqbal, M.F., Khan, I.A., 2014. Spatiotemporal land use land cover change analysis and erosion risk mapping of Azad Jammu and Kashmir, Pakistan. Egypt. J. Remote Sens. Space Sci. 17, 209–229.

Ismail, M.H., Jusoff, K., 2008. Satellite data classification accuracy assessment based from reference dataset. Int. J. Comput. Inf. Sci. Eng. 2 (2), 96–102, <http://www.waset.org/ijcise/v2/v2-2-16.pdf/>.

Kumar, J.A.V., Pathan, S.K., Bhanderi, R.J., 2007. Spatio-temporal analysis for monitoring urban growth – a case study of Indore city. J. Indian Soc. Remote Sens. 35 (1), 11–20.

Landis, J., Zhang, M., 2000. Using GIS to improve urban activity and forecasting models: three examples. In: Fotheringham, A.S., Wegener, M. (Eds.), Spatial Models and GIS: New Potential and New Models. Taylor and Francis, London, pp. 63–81.

Lassila, K.D., 1999. The new suburbanites: how American plants and animals are threatened by the sprawl. Amic J. 21, 16–22.

Lata, K.M., Rao, C.H.S., Prasad, V.K., Badarianth, K.V.S., Rahgavasamy, V., 2001. Measuring urban sprawl: a case study of Hyderabad. GIS Dev. 5 (12), 26–29.

Litman, T., 2007. Evaluating Criticism of Smart Growth. Victoria Transport Policy Institute.

Li, X., Yeh, A.G.O., 2002. Neural-network-based cellular automata for simulating multiple land use changes using GIS. Int. J. Geogr. Sci. 16, 323–343.

Li, X., Yeh, A.G.O., 2004. Analyzing spatial restructuring of land use patterns in a fast growing region remote sensing and GIS. Landscape Urban Plann. 69, 335–354.

Liu, J.G., 2000. Smoothing filter-based intensity modulation: a spectral preserve image fusion technique for improving spatial details. Int. J. Remote Sens. 21 (18), 3461–3472.

López Sándoval, M.F., 2004. Agricultural and Settlement Frontiers in the Tropical Andes: The Páramo Belt of Northern Ecuador, 1960–1990. Regensburger Geographische Schriften. Heft 37. Institut fur Geographie an der Universitat Regensburg, Germany.

Martinuzzi, S., Gould, W.A., Gonzalez, O.M.R., 2007. Land development, land use, and urban sprawl in Puerto Rico integrating remote sensing and population census data. Landscape Urban Plann. 79, 288–297.

Muñiz, I., Calatayud, D., García, M.A., 2007. Sprawl causes and effects of urban dispersion. In: Indovina, F. (Ed.), The Low Density City. Diputació de Barcelona, (cord), Barcelona, p. 307e347.

Páez, A., Scott, D.M., 2004. Spatial statistics for urban analysis: a review of techniques with examples. Geo J. 61, 53–67.

Pathan, S.K., Shukla, V.K., Patel, R.G., Mehta, K.S., 1991. Urban land-use mapping: a case study of Ahmedabad city and its environs. J. Indian. Soc. Remote Sens. 19 (2), 95–112.

Pendall, R., 1999. Do land-use controls cause sprawl? Environ. Plann. B. 26 (4), 555–571.

Portugali, J., Benenson, I., Omer, I., 1997. Spatial cognitive dissonance and sociospatial emergence in a self-organizing city. Environ. Plann. B. 24, 263–285.

Rafiee, R., Salman Mahiny, A., Khorasani, N., Darvishsefat, A., Danekar, A., 2009. Simulating urban growth in Mashad City, Iran through the SLEUTH model (UGM). Cities 26, 19–26.

Richardson, H.W., Bae, C.C., Baxamusa, M.H., 2000. Compact cities in developing countries: assessment and implications. In: Jenks, M., Burgess, R. (Eds.), Compact Cities: Sustainable Urban Forms for Developing Countries. Spon Press, London and New York, p. 25.

Serra, P., Pons, X., Saurí, D., 2003. Post-classification change detection with data from different sensors: some accuracy considerations. Int. J. Remote Sens. 24, 3311–3340.

Shahi, K., Shafri, H.Z.M., Taherzadeh, E., Mansor, S., Muniandy, R., 2015. A novel spectral index to automatically extract road networks from WorldView-2 satellite imagery. Egypt. J. Remote Sens. Space Sci. 18 (1), 27–33.

Soares, B.S., Cerqueira, G.C., Pennachin, C.L., 2002. DINAMICA – a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecol. Model. 154, 217–235.

Sudhira, H.S., Ramachandra, T.V., Jagadish, K.S., 2004. Urban sprawl: metrics, dynamics and modelling using GIS. Int. J. Appl. Earth Observ. 5, 29–39.

Taha, L.G., 2014. Assessment of urbanization encroachment over Al-Monib island using fuzzy post classification comparison and urbanization metrics. Egypt. J. Remote Sens. Space Sci. 17, 135–147.

Turner, M., 2007. A simple theory of smart growth and sprawl. J. Urban Eco. 61, 21–44.

United Nation, 2014. World Urbanization Prospects: The 2014 revision. <http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf/>.

Wang, W., Zhu, L., Wang, R., Shi, Y., 2003. Analysis on the spatial distribution variation characteristic of urban heat environmental quality and its mechanism – a case study of Hangzhou City. Chin. Geogr. Sci. 13 (1), 39–47.

Weng, Q., 2001. A remote sensing-GIS evaluation of urban expansion and its impact on surface temperature in the Zhujiang Delta, China. Int. J. Remote Sens. 22 (10), 1999–2014.

White, R., Engelen, G., 2000. High resolution integrated modeling of the spatial dynamics of urban and regional systems. Comput. Environ. Urban Syst. 24, 383–400.

Yanos, P.T., 2007. Beyond "Landscapes of Despair": the need for new research on the urban environment, sprawl, and the community integration of persons with severe mental illness. Health Place 13, 672–676.

Yeh, A.G., Li, X., 2001. Measurement and monitoring of urban sprawl in a rapidly growing region using entropy. Photogramm. Eng. Remote Sens. 67, 83–90.

Zanganeh, S.S., Sauri, D., Serra, P., Modugno, S., Seifolddini, F., Pourahmad, A., 2011. Urban sprawl pattern and land-use change detection in Yazd, Iran. Habitat Int. 35, 521–528.