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Assessing and Regenerating Proposed GIS Grid-based Geospatial Modeling Algorithms

Dr. Nermin A. Shoukry
Department of Geography, Faculty of Arts, Cairo University, Giza, Egypt.
nerminsh@hotmail.com

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Abstract

Since the rising of GeoComputation revolution in the late-nineties of the twenty's century in parallel with declaring officially the Geographical Information Systems "GIS" as an individual science discipline "GISc", some geographical scientific researchers dealt with Raster or grid-based Modeling to model various geographical phenomena in different perspectives for different objectives. This research is a new attempt to purify the modeling concepts from some misleading geographical published papers and unpublished M.A. theses & Ph.D. dissertations that dealt with grid-based spatial modeling irrationally. Recently, it was noticed that there is a conceptual confusion among many researchers concerning the GIS-based modeling environment. The confusion was detected from several perspectives. Firstly, there is a vague thinking among researchers in differentiating between GISystems (GISs) and GIScience (GISc) modeling approaches and between the rightful definitions of GIS-analysts and GIS-modelers. Secondly, differentiating between types of GIS-based models especially between "Ready-to-Use", "Programming-Modified", and "Programming Stand-Alone" models. Thirdly, the vigorously methodological misuse of the modeling procedures in which GIS-modelers should strictly follow. In this respect, this research shed lights on grid modeling algorithms of GIS Spatial Modeling - also called GIS-based Geospatial Modeling-. Three algorithms are chosen such as; Cartographic Modeling (CM), Surface Modeling Technique (SMT), and Impedance Surface Modeling (ISM). Empirically, modeling settlement/ urban growth change is chosen to be applicable to all selected and proposed modeling algorithms. Furthermore, it aims to offer a perusable study of these algorithms. Objectifying to study the concepts, characteristics, designs, structures, conditions, conceptual designed methodology, and procedures of both conventional and suggested modified algorithms. Furthermore, it focuses on producing critical assessment for traditional algorithm and then generating and proposing new modifications concerning the chosen application for each modeling approach. Finally, the study offers new geospatial modeling modifications to overcome the existing modeling algorithms' obstacles, limited usage, locality, performance deficiencies, and other modeling disadvantages.

Keywords: GIScience, Grid-GIS Spatial Modeling, GIS-based Geospatial Modeling, Cartographic Modeling (CM), Surface Modeling Technique (SMT), Impedance Surface Modeling (ISM), Settlement/Urban Growth Change Modeling.

I. Introduction

following the rise of the quantitative revolution in the mid-1950s of the last century, Geography -as a major scientific discipline- has been switched methodologically from being a totally theoretic that uses descriptive approach to be rigorously empiric using an analytical approach. A classical "Geography" is a field of science that describes mainly physical and human phenomena in the earth's surface; then representing, transforming, and codifying these phenomena cartographically into maps. In addition, multi-disciplines conversion is responsible of changing formal geography discipline from its classical state -that is academically was formed in the late eighteenth century- to a modern form. Therefore, marriage between disciplines is conceived of new generations of recent science trends. When overlapped with other disciplines such as statistics seven decades ago, many geographers were obsessively and extensively applied statistical methods in their researches transforming statistics conceptually from "*numerical*" to "*spatial*" statistical analyses. Thus, the term of "Spatial Statistical Analysis" has been emerged to analyze spatial geographical data. David Neft was a pioneer geo-statistician researcher who produced a systematic organization of statistical procedures to describe areal distribution focusing on point distributions. He discussed the concept of areal moments. He also developed spatial statistical measures such as: spacing, skewness, and kurtosis of various average position (different centroids), spatial dispersion, and surfaces. Moreover, he generated valid measures of statistical association of spatial variables (Neft, 1966). In 1996, David Unwin differentiate between three major terms, are as follows: Spatial Statistical Analysis, Spatial Data Analysis, and Spatial Data Modeling. As for the first term of *"Spatial Statistical Analysis*", the knowledge of a process is used to predict spatial patterns that might result as resultant observations. Here then the probability of any of this observed pattern is determined by an analysis of one or more of its realizations. Contrastingly, the second term of "*GIS Spatial Data Analysis"*, examines an observed distribution and attempts to infer the process that produce it. Hereby, the objective of this particular analysis is often attempted to find patterns in data that are meaningful in relation to the investigators' existing domain knowledge. Both first and second terms are different from the third term of *"Spatial Modeling"* in which the objective here is to produce realistic mathematical models of the type which used in many geographical application domains to predict spatial pattern (Unwin, 1996). In brief, the word *"analysis"* used alone refers to data querying and data manipulation in a GIS environment. Whereas *"spatial analysis"* refers to statistical analysis based on patterns and underlying processes. Thus, it is a set of methods producing refined results with spatial correlation. It involves statistical and manipulation techniques, which could be attributed to a specific geographic database (Burrough, 2001; Cucala *et al*., 2018; Paramasivam & Venkatramanan, 2019). Currently, all GIS software packages have modules that designed to handle spatial data analysis and also all the built-in data statistical-mathematical algorithms and modeling.

Concerning the development of both spatial data analysis and modeling, it has been evolved gradually in geographers' researches. Some geographers divide the evolution periods into two, one is "pre-computer or pre-GIS" and the other one is "post-GIS" (Getis, 1999). While, it can be divided according to the major spatio-temporal evolution break points. Thus, the researcher herself divide it to five periods as follows:

i. **The first period;** (from mid-1950s to late-1970s of the 20th century): It is termed as "***Statistical Spatial Data Analysis***" period that was emerged from "the Quantitative Revolution" with the convergence of both disciplines of statistics and geography. The last decade of this period witnessed the birth of the Canadian Geographical Information Systems (C-GIS).

ii. **The second period**; (from mid-1980s to mid-1990s of the 20th century): It is occurred by merging computer aided software package system with the former two disciplines of geography and statistics. This period is flourished as a "***GIS Spatial Data Analysis***". A British geographer "Stan Openshaw" is termed this period as "***The GIS Revolution***" (Openshaw, 1995). The terminology of Geographical Information Systems (also GISystems or GISs) was first coined in the 1960s, but was evolved and flourished technically by the late-1980s. Basically a "GISystems" is introduced as a widely adopted specialized software application (tool-package) which is concerned with the use of regular and large size digital data to represent mainly space and time. Customarily, it is defined as a computer-based information multi-internal-systems that attempts to capture, input, store, manage, manipulate, analyze, and cartographically display an output of spatially referenced data for solving many complex spatially geographical problems. Therefore, the spatial data is the main key element in a GIS environment. Another key element, is the applied analysis itself. In 2006, Fischer argued that a GIS spatial data analysis focuses on detecting patterns and exploring and modeling relationships between such patterns in order to understand processes responsible for observed patterns (Fischer, 2006). This period was nourished with expanding spatial data methods and ready-to-use spatial data models that are built-in the commercial GIS software system itself. Yet, all built-in methods, models, and programming software (if founded) are still parametric *"statistical-mathematical"*-based. Some parametric models in a GIS environment can predict missing values or even future values by using number of fixed parameters with respect to the sample size.

iii. **The Third period**; (from late-20th century to the first decade of the 21st century): it is termed as "***GeoComputational Spatial Data Modeling***" period. This period is considered as the third revolution of modern geography. The researcher term it also as "***The GIScience-GeoComputation Revolution***" or "***GISc-GC Revolution***". Initially, the convergent disciplines tend to be expanded more to include computer science and information science in this period. Geographical Information Science (also GIScience or GISc) and GeoComputation (also GC) are two parallel co-evolution disciplines that have emerged in this period.

Back in 1983, Dobson was the first to plant seeds of the rising discipline of GC in his published paper entitled " Automated Geography". He sheds new light on defining it as the eclectic application of computational methods and techniques to portray spatial properties, to explain geographic phenomena, and to solve geographic problems (Dobson, 1983). A decade later, in 1992, Michael Goodchild was the first geographer to coin the term GIScience academically in his published research paper. He debates that GIScience is considered as the development and the use of theories of spatial data, methodological approaches, technology, data structures, data modeling, algorithms, and processes for understanding geographic processes, relationships, and patterns (Goodchild, 1992; 2010). Thus, the GIScience discipline has been developed out of the maturing GISystems. Collaterally, GeoComputation (GC) has been officially born as a new discipline just as well and grew up to find its place in the scientific arena. The first international conference on GeoComputation was first coined in the year of 1996 in Leeds in UK. Inspiring its name from the work of the GeoComputational proponent "Stan Openshaw" -(Openshaw was titled by Goodchild and many geographers as "father of spatial data science")- who states that it is absolutely fundamental that we can develop tools able to detect, by any feasible means, patterns and localized association that exist within the map (Openshaw & Abrahart, 1996; Openshaw, 2000; Goodchild, 2022).

iv. **The fourth period;** (is flourished and became commonly used in the second decade of the 21st century): it is termed as "***Geospatial Artificial Intelligence (GeoAI) Data Modeling***" period. This period is considered as a higher level evolution of the previous one. It can be divided into two phases: the first is based on the linearity approach in programming that consists mainly of parametric modeling algorithms, while the second is based on the non-linearity approach in programming that depends on nonparametric modeling algorithms. Both phases are totally independence computer programmed that might be processed individually or could be integrated with some commercial (GISs) softwares. As for parametric models, it can predict future values using only any number of previously specified parameters. While on the other hand, the nonparametric machine learning intelligent algorithms are rather flexible as they are not making assumptions (sometimes have weak assumptions), but they are free to learn any functional form from the training or sample data. This evolution period has its benefits from the usage of nonlinearity approach with its nonparametric machine learning algorithms, in a way which suits for more complex geospatial data that can result in higher performance models for accurate future prediction. The most common evolved stand-alone AI techniques in this period are: Fuzzy Models (FM), Artificial Neural Networks (ANN), Cellular Automata (CA), Genetic Algorithms (GA), Multi-Agent Systems (MAS), Swarm Intelligence (SI), Reinforcement Learning and Hybrid Systems, Bayesian Networks (BN), and Data Mining (DM).

v. **The fifth and last period**; (is flourished in the past few years up till the current published date of this research). It can be termed as "***Integral GeoAI Modeling***" period. To achieve more robustly machine learning algorithms that have higher performance, the integration between intelligent models is required. This association between AI models can be translated methodologically in different ways; as loose integration approach, stand-alone models, or constrained intelligent models. However, insufficient number of researches have been worked on integrating GeoAI modeling algorithms. In the field of Settlement/Urban growth expansion prediction, much less research contributions have been examined on integrating some highly performed predictive intelligent models such as ANN and CA modeling up till now.

Quantitatively or computationally oriented spatial analyses involve rigorous procedures of model building and validation, thereby were suitable for solving complicated spatial problems. Methodologically, there are four types of modeling such as descriptive, analytical (explanatory), predictive, and prescriptive (normative). Starting with the minimum "information" and ending with the maximum "optimization", these modeling types must consider answer basic research questions for any studied spatial phenomena as follows: what happened? why did it happen? what will happen? and how can we make it happen, respectively.

Grid-based or Raster-based geospatial data modeling is considered as an essential pillar of the grid analysis. Differentiating between Raster-based spatial modeling types is regarded as fuzzy conceptual thinking in the geographical arena in the world, especially among geographers of the Middle East countries. Recent advances in computer based GISs and GISc especially in grid analysis, have created a new arena for precision spatial analysis that provide useful environment to create algorithms for conducting spatial modeling. Grids work well for spatial modeling especially for the analysis of change over time such as settlement/urban growth in our case. Perceptively, spatial modeling uses as well analytical procedures to abstract and simplify complex geographic systems such as urban growth as previously mentioned, which is one of the most complex and multi-faceted systems in cities and urban areas. Using gridded data has one major advantage, regarding the continuous field model provides a much richer suite of truly spatial analysis operations that have many practical uses. Choice of appropriate data model can be the critical factor for the success or failure of an information system (Burrough & McDonnell, 1998; Worboys & Duckham, 2004). In addition, the raster organization is well suited for modeling spatial continua, particularly where an attribute shows a high degree of spatial variation, such as data on satellite images. The regular spacing of pixels in a lattice is ideal for calculating and representing spatial gradients (Bonham-Carter, 1994).

Spatial modeling algorithms usually use geographic data to achieve one of three major objectives such as describing, simulating, and predicting settlement/urban growth or achieving all together simultaneously. For example, a model could simulate the movement of such growth under a given set of conditions to predict its direction and suggest the appropriate strategies to be taken in near or far future. Most of these personal developed modeling algorithms have been generated with specific calibration and conditions that suit its own developers based on their original geographical environments backgrounds. Therefore, when used, empirically tested and applied by other researchers in different geographical study areas and environments all over the world, they obtained inaccurate final outcomes and results.

One main objective of this research is to purify the modeling concepts from some misleading published papers or even some unpublished M.A. Theses and Ph.D. Dissertations that dealt with spatial grid modeling irrationally especially in the Middle East or other Developing countries. In this respect, the research firstly sheds light generally and methodologically on the principles and steps of modeling with GISs/GISc in which GIS-modelers should strictly follow. Mainly, a grid modeling type such as Grid-GIS spatial modeling (Geospatial modeling) is aimed to be studied with its different selected algorithms. Three modeling algorithms are chosen such as; Cartographic Modeling (CM), Surface Modeling Technique (SMT), and Impedance Surface Modeling (ISM). In this research study, modeling settlement/urban growth change is chosen to be applicable to all selected modeling algorithms. Moreover, the research aims to offer a perusable study of these ready to use algorithms -that are built-in and existed in many commercial GIS softwares- with their possible proposed programming modifications that is directed toward the chosen application. Furthermore, it aims to objectify the study of the concepts, characteristics, designs, structures, conditions, and procedures of all proposed algorithms. As well as focusing on producing critical assessment, then generating and proposing new methodological and conceptual modifications for each modeling approach to overcome the existing modeling algorithms' obstacles, limited usage, locality, performance deficiencies, and other existing modeling disadvantages.

II. Research Methodology

This research examines the chosen grid-based spatial data modeling algorithms that is related to a GIS-based raster data format. The raster spatial data in a GIS software environment is dealing directly with the raster analyses interface and has been operated by using grid operations that is built inside any GIS commercial software as mentioned above, whether by using the grid analyses toolbox, or by using "the ready-to-use" modeling builder that depends on specifying different and various factors and parameters according to the different choices and decisions of the different analysts (user-defined decisions), or even by using the built-in programming software such as for example "Python" that is built-in as a separate interface inside a commercial software like ArcGIS. Figure (1) displays the overall research methodology that is outlined in the flowchart diagram depicted below. It is structured in four main procedure steps of overall methodology. The first is to set the context by dealing with the broad concepts, compositions, and characteristics of the selected conventional Grid-based spatial modeling algorithms with their traditional and current practical different physical and human geographical applications to be achieved. The second step of the research procedure is to assess and criticize each model by analyzing, evaluating, and explaining the shortage of the conventional modeling algorithm. While, the third focuses on explaining the proposed conceptual modifications of the studied three modeling approaches, stating their basic new concepts, conditions, structures, suggested programming designs, and the proposed new methodology procedures for the chosen applicable task. Finally, it offers a proposed functional block diagram that depicts the detailed proposed new methodological procedures that ends with producing a final resultant regenerated modeling for detecting and displaying a final grid layer output of settlement/urban growth expansion, patterns, involving factors, growth movements and trends that differs and varies from one suggested model to another according to the differences of the structures and programming designs of the three proposed modeling approaches.

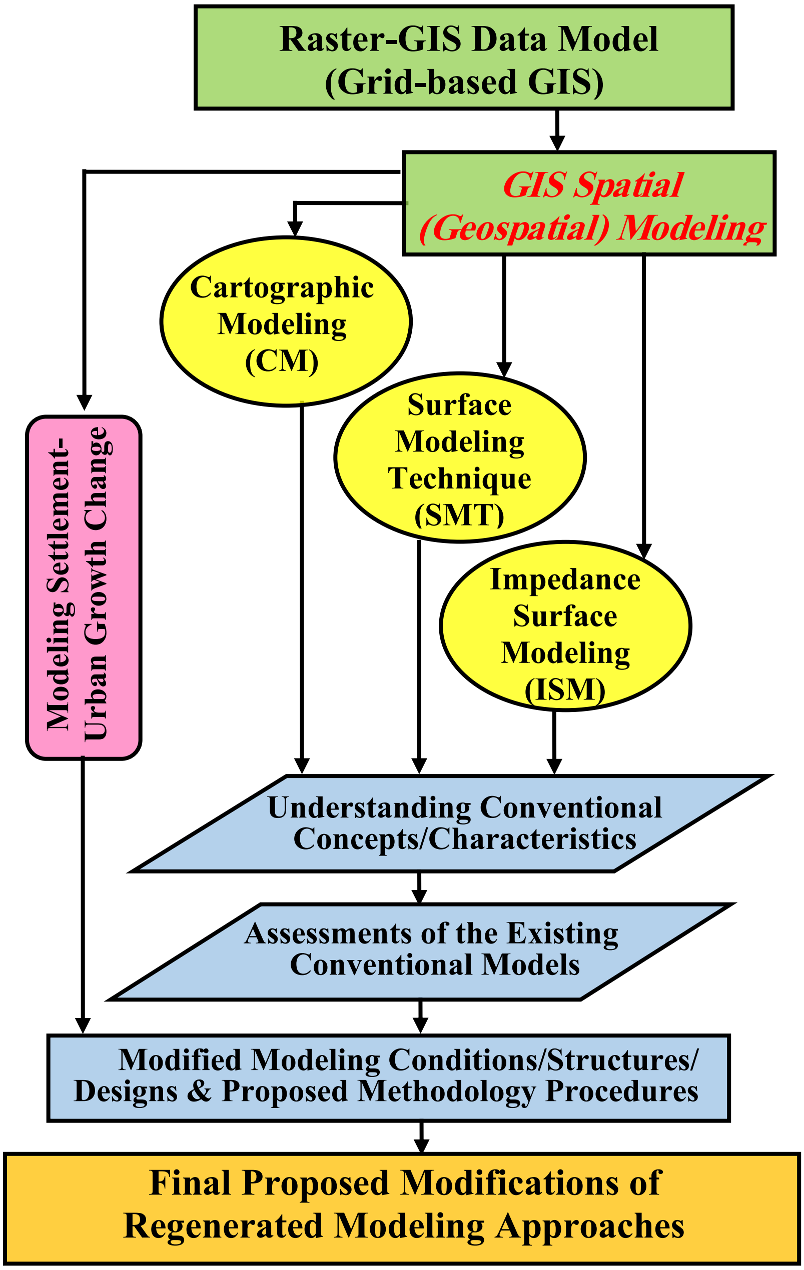


Figure 1. Flowchart of the overall research methodology.

III. Literature Review

The following literature review provides the necessary background of the original and conventional modeling approaches. Stating their concepts, their usage and traditional applications, and their modeling capabilities in different scientific fields. Moreover, it provides significant reviews of some research literatures that attempts to apply the selected algorithm models or to create new modeling algorithms to achieve the stated researchers' objectives. Therefore, this reviewed literature builds the foundation of this research. Thus, it is directed toward the fundamentals of five main research subjects. These subjects are: modeling with GIS environment, Grid-GIS spatial modeling for settlement/urban growth, Cartographic Modeling Approach (CM), Surface Modeling Techniques (SMT), Impedance Surface Modeling (ISM). Each related literature review will be embedded and demonstrated sequentially in each following subject and modeling approach in the coming text.

IV. Modeling with GIS Environment

In simple words, a model is a representation of reality. Originally, spatial models are created as a simplified, manageable view of reality to help researchers to describe, understand, explain, simulate and predict any geographical phenomenon following the methodological types of models that are mentioned above. When constructing models for analyzing spatial phenomena, several factors should be taken under considerations. In this regard, Models have different classification categories and types according to the differentiating factors (Figure 2). Initially, one major factor, is specifying firstly the type of modeling usage that gradually starting with the ordinary GISystems user or analyst and ending with the highly skilled GIScience modeler. This modeling category can be divided into five main types of models such as: firstly, the ready-to-use models that built-in the system itself. Secondly, is the programming modified models that is modified by the researcher and by using either the system built-in programming language or by using an independent programming language software such as Java or C++ for example. Thirdly, is "loose coupling" modeling which implies that GIS and modeling software are coupled sufficiently to allow the transfer of data, and perhaps also the results in the reverse direction. The fourth type is the close-coupling models which implies that both GIS and the created model read and write the same file through a common interface. Finally, the highly sophisticated stand-alone models that often exist as separate software programs, these types of models are termed and referenced by the name of its own creators such as Keith Clarke CA model for example. After delineating and choosing the proper type of modeling according to the user's/analyst's or modeler "GISs or GISc" experience and capabilities, the second category of modeling types should be recognized and examined. This category is concerned with specifying the methodological models and its subdivision types as it has been explained and mentioned above. Following the methodological perception of modeling types, models can be classified into other different categories according to scale, dimensional space, conceptual, mathematical, and operational perceptions (Steyaert, 1993; Goodchild, 1993).

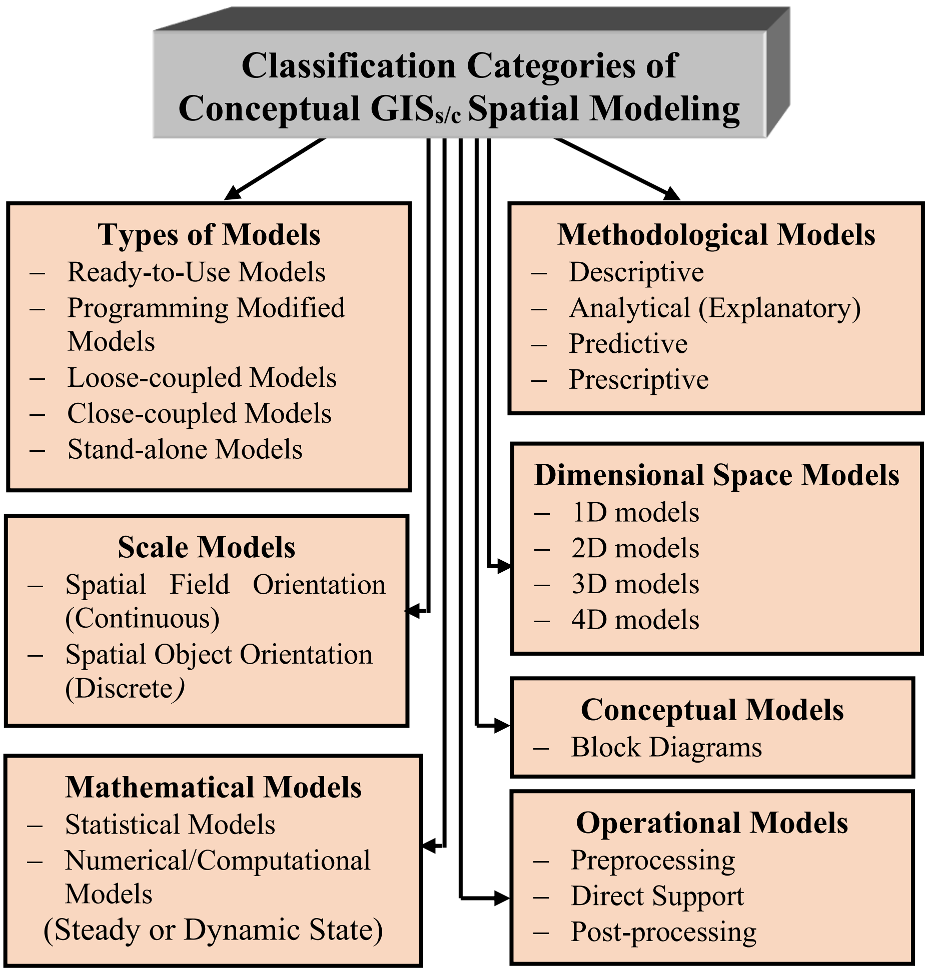


Figure 2. Classification Categories of Conceptual GISs/GISc Spatial Modeling.

Regarding the scale factor, this modeling perception can be divided mainly into two types such as: spatial field orientation and spatial object orientation models, while the dimensional space can be divided into four types such as: 1D, 2D, 3D, and 4Dimensional space. Whereas, conceptual models are frequently used in the modeling process in block diagrams which is a graphical representation that show major systems, processes, and qualitative interrelationships between subsystems. The mathematical perception of modeling can be further classified as either statistical or numerical (computational). Both statistical and computational models can be further subdivided into either "steady-state" or "dynamic-state" models. Finally, the operational perception of modeling in a GIS environment contains three main operational procedures such as: data preprocessing, direct support for analysis and GIS modeling, and post-processing of results. Concerning the first O-procedure, it can consist of some basic operations such as reformatting, change of projection, resampling, and generalization. While, the second is considered as the core of modeling that deals with the forms of analysis, calibration of models, simulating or forecasting and prediction that mostly could be handled as either by using the "user-friendly" instructions and ready-to-use parametrical models that built-in inside any commercial GIS software, or by using the "not user-friendly" modeling such as "loose coupling" or "stand-alone" modeling. As for the third and final post-processing of results O-procedures, it includes such operations as reformatting, measuring precisions and accuracies, tabulation, report generation, and mapping or dynamic displaying. Eventually, some other remaining factors should be taken under consideration to be specified, examined, and added to the main modeling categories such as: the model building, delineation of geographic units, structural factors, and the spatial factors.

V. Grid-based GIS Geospatial Modeling

The collection and analysis of spatial data became easier with the advance of Geographic information systems/science ($GIS_{s/c}$) and remote sensing (RS) algorithms. As mentioned earlier, the origin of spatial analysis lies in the development of quantitative and statistical geography in the 1950s. Spatial analysis was originally based on the application of the available statistical methods to spatial data. Later, it was extended to include mathematical model building and operational research methods. The geographical information revolution demands a new style of spatial analysis that is GIS appropriate and GIS proof (Openshaw, 1991). Evolutionary, the GISystems, GIScience, Geoinformatics, and Geomatics (sometimes Geomat.) along with Geocomputation and GeoAI are used today extensively for managing various applications such as the rapidly growing urbanization of our cities and villages (Kumar *et al*., 2011).

Concerning GIS spatial (Geospatial) modeling for settlement/urban growth applications; Goodchild (1987) explains the spatial analytical perspective on GIS in his pioneer study in this field. He focuses on representing storage methods which is organized around the raster versus vector debate and the need to represent two spatial dimensions in one. Masek *et al*. (2000) discuss the dynamics of urban growth from Landsat observations using Washington D.C area as a case study. They use raster spatial modeling technique to generate a time series of growth in the study area for four Landsat scenes with different spatial resolution. Herold *et al*. (2003) explore the combined application of remote sensing, spatial metrics, and spatial modeling to the analysis and modeling of urban growth in Santa Barbara, California. They suggested a spatial model that allows a spatial forecast of urban growth to the year 2030. Their result illustrates the utility of modeling in explaining the amount and spatial pattern of urban growth. Haak & Rafter (2006) examine in their study, the difference of the change analysis between two dates to model future urban growth by using land use /land cover (LULC) maps of the study area. They use two sets of satellite data with different spatial resolution such as CORONA and IKONOS. Kumar *et al*. (2007) investigate, detect, analyzed, and mapped the spatial patterns and physical expression of urban development and sprawl on the landscape by adopting Grid-GIS technology and RS data. Geospatial modeling on a GIS environment reached its peak with exploring suitability analysis for settlement/urban growth to help the users to identify the best possible locations for the growth by defining different types of criteria, parameters, and weights by them depending on GIS built-in ready to use modeling techniques tools (Joerin *et al*., 2001; Javadian *et al*., 2011; Alexander *et al*., 2012; Kumar & Shaikh, 2013). Furthermore, in the past two decades the Raster-GIS data models with the infusion of remotely sensed data have been risen and extensively employed for urban modeling to simulate the urban land cover changes and urban sprawl. In this respect, settlement/urban growth change is chosen to be potentially experimented and demonstrated in three different selected Grid-based Geospatial modeling approaches as follows:

1. Cartographic Modeling (CM) Approach

The term "Cartographic Modeling" was first coined by Charles Dana Tomlin and Joseph K. Berry (1979) to specify and characterize the process of using combinations of commands to answer questions about spatial phenomena. More formally, the CM approach was implemented theoretically and conceptually -but has not been commercially termed yet at the time - in a raster GIS in the year of 1983. Tomlin (1983) introduces – in his PhD dissertation – map algebra operators based on how a computer algorithm obtains data values by processing raster surface. He identifies four fundamental function classes: local, focal, zonal and global functions. Applying a raster GIS modeling, it has one major advantage with raster representation in which each attribute is recorded in a separate overlay. Therefore, any mathematical operation performed on one or more attributes for the same cell can be easily applied to all cells in the overlay. This means that one can use exactly the same algebraic notation to operate on gridded data as on single numbers (Burrough & McDonnell, 1998). The method is called ***Map Algebra*** (Tomlin, 1983, 2013) that can be defined as the formal language for raster analysis that form the basis of raster operations, while the procedure of using algebraic techniques to build models for spatial analysis is called ***Cartographic Modeling***. Buttenfield & Charisoulis (2021), states another simple definition of CM; that "Cartographic Modeling is an integrated sequence of spatial data processing tasks that organize, combine, analyze, and display information to answer a question".

In a GISs platform, basically a cartographic model (CM) -in its simplest form- is a set of mapped data registered with respect to a common study area in any geographically physical or urban spatial data applications. It is a collection organized in such a way that all of its data pertain to a common geographic locality. This locality is then referred to as the model's study area (Tomlin, 2013). Since the appearance of this GIS spatial modeling technique and the flourish of its scientific terminology that was officially coined by Tomlin in 1990, Some researchers argue that CM approach is considered as the heart of the GISs raster modeling framework. It is also classified as the best standard methodology and practice within the GISs modeling community (Tomlin, 1990; DeMers, 2002). Therefore, almost all raster-based commercial GIS software packages have adopted this standard approach as well as its terminology.

Berry (1987) describes the fundamental classes of operations used in computer-assisted map analysis. He develops a generalized framework for cartographic modeling. He also develops the concept of the "Map-Ematics" – it has the same characteristics of "Tomlin's Map Algebra" – which established cartographic modeling as an accepted methodology for the processing of spatial data. Hodgson & Gaile (1999) present in their article the fundamental directional operators and demonstrate their development for several surface-oriented applications, such as: mean and dispersion in neighborhood surface orientation by using cartographic modeling approach. Effat *et al*. (2012) have modeled the potential risk of sand dunes encroachment related to their terrain characteristics in Sinai Peninsula, Egypt. Their result is the establishment of a risk map that is essential for land use planning and environmental management. Pareta (2012) examines how using CM approach, the ability to make representative geospatial representations of maps that help with modeling and studying complex geo-spatial inter-relationships that can create a more responsive urban growth strategy. Petkov & Bandrova (2020) classify cartographic modeling according to four main characteristics as follows: ***the content*** (general, thematic, specialized), ***the dimensionality*** (2D, 2.5D* , 3D, 4D, multi-dimensional), ***the material of production*** (paper/hard-base, digital, anaglyph "carved in low relief", 3D holographic, web map), and ***the types of reality*** (virtual, augmented, physical). Their proposed classification schema offers a simple method to select the suitable CM that can be used to analyze and visualize a research data set.

According to the mentioned above concepts, one can simply define a primitive Cartographic Modeling (CM) as the process of combining maps together. In other words, it is the spatial analysis and processing steps or procedures that is based on several superimposed map layers and following sequence of spatial data operations of map algebra in which cartographic models are generated in a GIS environment.

In some specialized GISs commercial software companies such as "Esri" that owns an ArcGIS software package, raster analyses with its cartographic modeling implementation depends crucially on Tomlin's Map Algebra (MA) method that forms the basis of raster tools such as Spatial Analyst-Toolbox whereby MA-Raster Calculator is applied. It offers an efficient tool to use mathematical and logical operators. These operators are: **Arithmetic** (+, −, ÷, ×, mod. [modulus-integer only-]), **Relational** (>, <, >=, <=, and many more), Boolean (Boolean logic = true/False or 1/zero), **Bitwise** (make all nonzero values will be converted to their binary equivalent, *i.e.* [<<1 of the value 2 = 4]), **Combinatorial** (it shares with Boolean operators, *i.e.* AND & OR), **Logical** (compares values based on pairs of matrices *i.e.* contained in "IN" & difference "DIFF"). These operators can be combined with higher-level procedures called "functions" such as local, focal, zonal, and global. Yet, the CM construction were implemented by different users, and operationally differs from one researcher to another according to their deferential various fields of interest, to their own methodology designs, and to their

* 2.5D map (also known as a perspective map or bird's-eye view map) is represented in an oblique perspective that have a slanting or sloping direction. It simulates the appearance of 3D map whereas in fact it is not.

selected spatial operations. Following and operating these sequential procedures, is considered by many GISs users as an exhausting, stressful, and time consuming task.

Therefore, "Esri" have extended the usage of CM in their ArcGIS-Spatial Analyst software package user interface to ease and simplify the modeling process. They create a user-friendly "ModelBuilder" platform that is built-in the raster-GIS environment into the software itself (Figure 3). It is an extended Cartographic Modeling into a visual ready-to-use programming capability, permitting a user with no programming background nor skillful use of Map Algebra and query language to assist him for building workflows to design and accomplish his model sufficiently. It easily allows a user to drag and drop icons representing spatial data files (raster-GIS layers) and GIS operators onto a graphical window, to link them graphically to represent a desired processing sequence, and then to validate and run the resulting geospatial model in the ArcToolbox interface in ArcGIS. Thus, the ModelBuilder is considered as an easy-to-use application for creating and running sequential steps and tools in connected workflows. Although CM do not demand weighted parameters (Buttenfield & Charisoulis, 2021), the ModelBuilder allows identifying parametrical specifications, prioritize

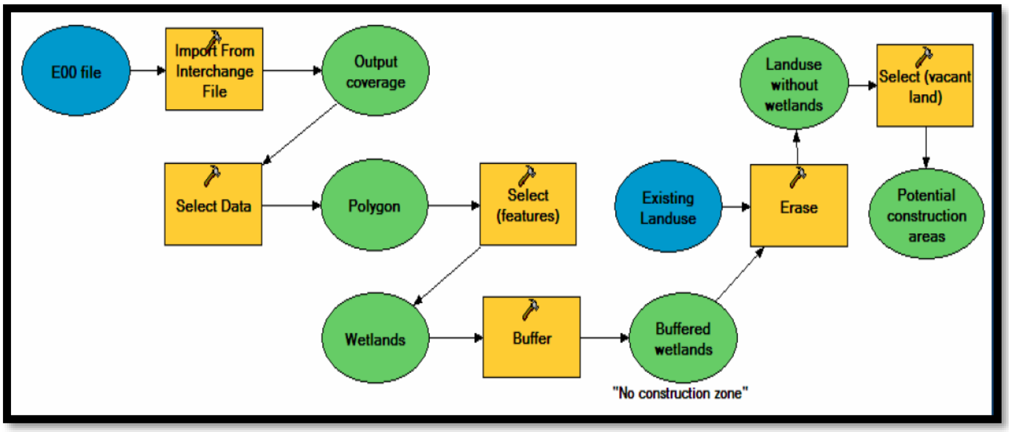


Figure 3. An example of user-friendly ModelBuilder ready-to-use workflows in Arc Toolbox interface in ArcGIS software (source: Esri, 2020).

possibilities, or weighted the relative importance of criteria and refine a final analytic result. Figure 4 shows an applicable example of a created geospatial urban development structural model by using ArcGIS-ModelBuilder platform to analyze and evaluate spatial suitability to deduce future urban growth in a study area based on selected 11 variables to build a geospatial model (Abdou & Shoukry, 2024).

1.1 *Understanding CM in Settlement/Urban Applications*:

A grid-GISs based cartographic modeling has the ability to create either simple or sophisticated spatial models for many different geographical problems. The most common settlement geography applications in raster mode are: measurement, calculations, grid statistics, suitability analysis, the greatest suitability for site location, network analysis, risk and crisis management, cost surface analysis, shortest route analysis, and change and time series analysis. GISs have the ability to merge spatial datasets from quite different raster-based sources, then displaying, manipulating, spatially analyzed these data combinations in a way that can often lead to obtain best decision deduction based on understanding the analytical interpretation of spatial phenomena such as settlement growth. Land use/Land cover (LULC) change model use cell statistics to calculate and visualize temporal changes over time to identify changes and thus depicting its growth.

1.2 *Conditions of CM approach*:

The conventional spatial Cartographic Model approach has three basic conditions as follows:

i. The map operations must interact with one another.
ii. Each individual operation performed on coverage must have - as a purpose- the creation of a result, usually another coverage that can be used by the next operation.
iii. The next operation may be a further manipulation of the same coverage in order to isolate certain map variables, or it may operate on a second coverage, perhaps as a map overlay operation.

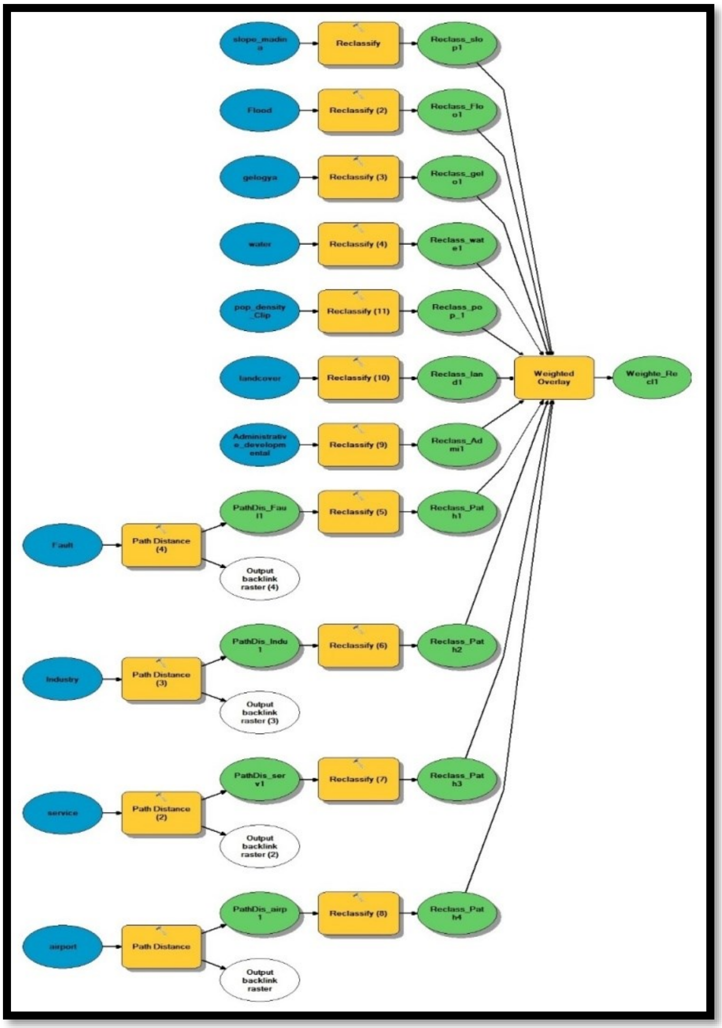


Figure 4. An applicable example of Land Suitability Analysis Modeling for suitable Urban Growth Development in Al-Madinah Al-Munawarah by using CM-ModelBuilder in ArcGIS software (source: Abdou & Shoukry, 2024).

1.3 *Map Algebra*:

Cartographic or "map" modeling is carried out in GIS using map algebra that varies in syntax and implementation from one system to the next. We can define also as a language that defines a syntax for combining map themes by applying mathematical operations and analytical functions to create new map themes. In a map algebra expression, the operators are a combination of mathematical, logical, or

Boolean operators, and also spatial analysis functions such as: shortest path for example. Moreover, map algebra mainly provides an easy-to-use and powerful way to define geographic analyses as algebraic expressions. This allows users to take their real-world data and apply algebraic functions to derive new results (ESRI, 2013).

The methods of *Map Algebra* mean that the user needs only to specify the spatial operations to be used and the names of the source overlays and the result, the computer program then applies the operation to all the cells in the overlays. This makes it very easy to write computer models as sequences of computations, and makes the extension of formerly points models to two-dimensional space very easy (Burrough & McDonnell, 1998). For example, the command: ***NEW-MAP* = *MAP-1* + *MAP-2* + *MAP-3*** is all that is necessary to compute the sum of the values of the attributes on the three mentioned overlays in the grid-based approach, and the command: ***NEW-MAP* = (*MAP-1* + *MAP-2* + *MAP-3*) / *3*** to compute the average value. These two examples compute new values on a cell-by-cell basis: they are known as *point operations*. Additionally, by using the concepts of surface differentiation and smoothing, it is possible to compute new attribute for a given cell as some function of the attributes of cells within a certain spatial neighborhood: it is known as *spatial operations*, that it may contains spatial functions such as interpolation and spatial filtering for example. This mathematical structure forms a conceptual framework easily adapted to a variety of applications in a familiar and intuitive manner (Berry, 1993). In the case of measuring the Urban Growth Rate (UGR), a basic mathematical structure is used by setting a simple mathematical equation. It is stated as follows:

UGR = {(final growth - initial growth) ÷ (initial growth)} ×100

Geographers use basically this equation to calculate and measure the percent change in urban growth in any area. Another mathematical structure is developed by Shoukry in 2004; Abdou & Shoukry in 2024 to measure the future prediction of such growth as follows:

$$S_{t+1} = - S_t [(Tr_s / 2) + 100] / [(Tr_s / 2) - 100]$$

Where: S_{t+1} (the expected future growth), - S_t (the existed built-up area), **T** (selected time interval or number of years of future prediction), r_s (selected growth rate). All of these mathematical equations can be infused in GIS Geospatial analyses by using Map Algebra operations in cartographic modeling to mathematically calculate settlement/urban growth change rate and even to predict the future growth.

1.4 *Proposed CM Approach in Urban Growth Application*:

To understand the nature of this approach, figure 5 displays a proposed conceptual CM time series approach for depicting and analyzing the growth development and expansion of a built-up area in a city. Mapping the growth change in this approach is based on integrating remotely sensed data analyses with grid-GIS geospatial analyses. In addition to the previously mentioned CM conditions, two more conditions must be applied. The first: it is obligatory to apply all processing and analysis procedures on grid-based data with no vector layers infused. The second: it is obligatory to apply this approach to process and compare the growth development between two different dates ($\geq d_{n=2}$) -as a minimum number of time series datasets- for any given location. The proposed procedures are as follows:

i. The proposed conceptual CM time series approach has two main phases. The first is the remotely sensed data processing and analyses while the second is the GIS geospatial processing and analyses.

ii. The remote sensing phase starts with the input of multi-temporal satellite imagery data sets. To monitor the settlement/urban growth, time series satellite images that have same anniversary date with fixed time intervals of chosen number of years are preferably selected.

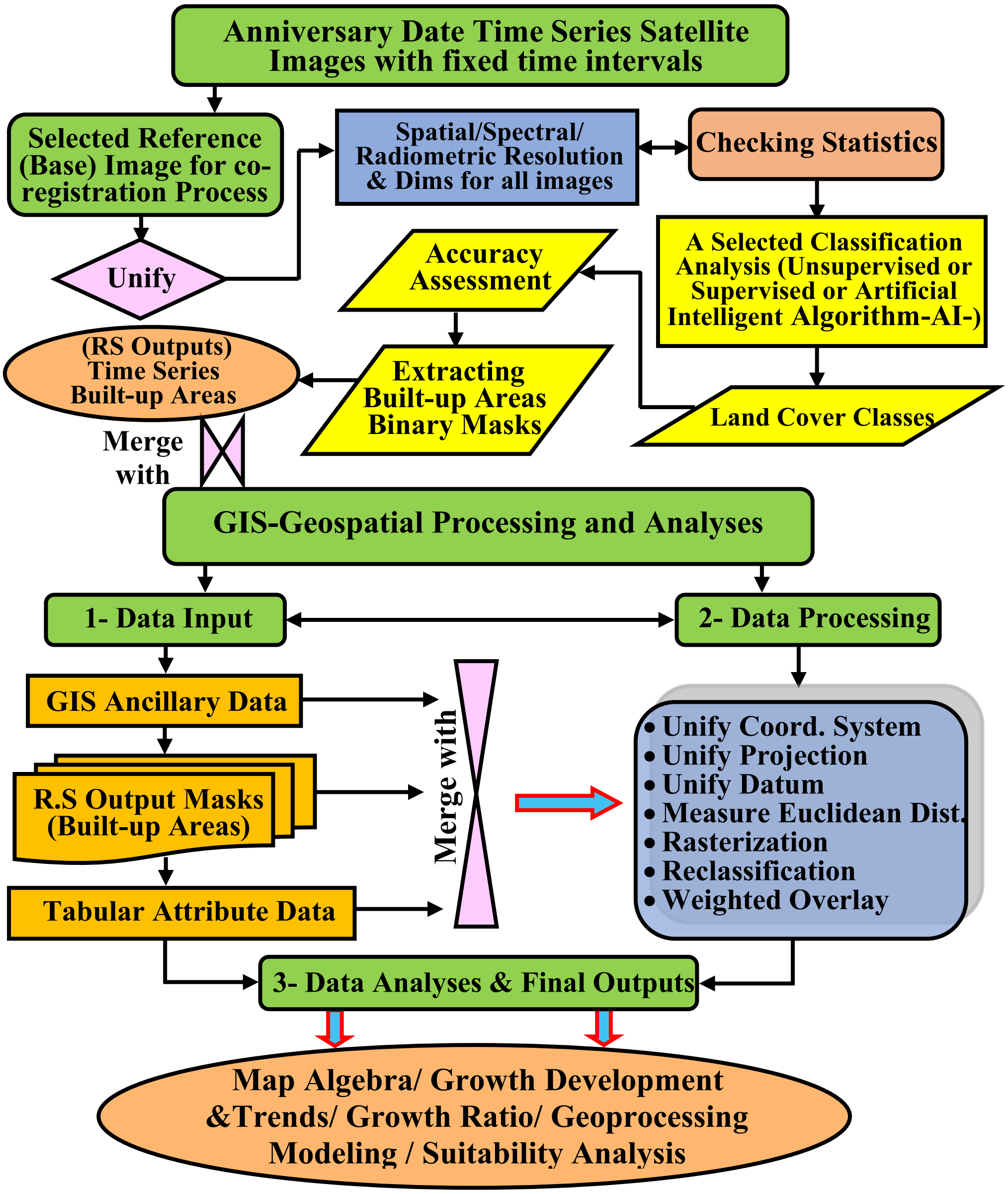


Figure 5. A proposed Conceptual Cartographic Modeling Time Series Approach for Urban/Settlement Growth Development and Expansion.

iii. Among the imagery datasets, a selected reference image with no positional error was checked statistically and spatially. It is chosen to be a base image for a co-registration process between the base and all other images of the study area to prevent any positional error in all datasets. To unify all images' spatial dimension, a spatially subsetting procedures is applied. Moreover, preprocessing analyses are required to unify the spatial, spectral, and radiometric resolution for all images. Before applying any further analysis, statistics of each image should be examined carefully.

iv. A selected classification analysis such as: unsupervised, supervised, or artificial intelligent algorithm is analyzed to obtain time series land cover (LC) classes of the study area. It followed by measuring accuracy assessment for each resultant LC. The first phase ends with extracting built-up area binary mask of each classified image to be prepared to be merged with the second phase of the proposed approach.

v. The GIS geospatial processing and analysis phase is divided into three procedures. The first is the GIS data input, the second is the data processing, and the third is the data analyses and final outputs.

vi. The GIS data input includes the remotely sensed output masks of time series built-up areas. Moreover, it contains GIS ancillary data such as: geology, hillshade, slope, growth obstacles' land cover (i.e. water bodies), and population density. In addition, tabular attribute data is included. Finally, all different sources of data input are merged with the second procedure.

vii. The data processing for all geospatial data layers is accomplished by unifying coordinate system, projection, and datum for all data input of different layers to measure Euclidean distances, rasterization process, reclassification process if needed, and also applying other operations such as weighted overlay.

viii. The final GIS procedure is to apply all data analyses that related to settlement/urban growth such as: using map algebra, geoprocessing modeling, and suitability analysis if needed. The final outputs of the proposed modeling approach display the growth development, growth trends according to major geographical directions, growth ratio, and the spatial suitability of potential growth according to the user's different growth scenarios (user-defined parameters).

2. Surface Modeling Techniques (SMT)

Scholars have made efforts to understand and apply the process and mechanisms of Surface Modeling Techniques (SMT). Their researches tend to be specialized towards the continuous surface generation techniques in physical studies (*i.e.* Physical Geography studies) applications, such as air pollution, DEM construction, surface flooding, temperature, contouring, and other 3D applications: azimuth or orientation, steepness of slope, shape or form, and intervisibility. On contrast, there is lack of applying STM in urban studies. Bracken (1994) uses SMT to represent population-related social indicators in Great Britain. He argues that the representation of population and population-related phenomena, could best be done using a surface model approach. The implementation of the proposed raster model is capable of providing a good approximation to a spatially continuous estimate of population from census or postcode sources. Luo (2006) investigates in his doctoral dissertation the spatial structure of transitional Chinese cities through displaying an urban population distribution using census data and advanced GIS techniques. He develops an alternative analytical framework to investigate the urban population distribution and spatial structure through a flexible scheme of generating raster population surface. Luo & Dennis Wei (2009) generate a probability surface of urban growth from raster calculations among the parameter and variable surfaces that provide an urban growth patterns scenario. Maishella *et al*. (2020) present a study that analyzed urban built-up areas development and its correlation with land surface temperature (LST) to determine the direction of the regional development in their study area. They examined a multispatio-temporal data analysis that contained spectral transformation and classification analysis of built-up areas. They combined urban development and building density correlation analysis with surface analysis of LST to end with a strong correlation and significant t-test result with classification overall accuracy of 88.4%. Yun *et al*. (2023) develop a three-dimensional urban surface model (3D-USM) and conduct a spatiotemporal thermal comfort simulation with respect to urban street direction. Their proposed model is simulated the thermal environment in complex urban environments efficiently using simple input data and they experienced their model on three urban streets with different rotation angles. Their results suggest that planners should considerably simulate spatiotemporal thermal comfort with respect to the streets different angles to create an effective sustainable city.

2.1 *Understanding SMT approach*:

The process of converting point data to data structures that represent a continuous surface is called surface modeling – it is also called contouring when dealing with topographic surface –. There are direct links between the data model and the data type used to represent a geographical phenomenon and the kinds of analysis that can be carried out with it. If no clear entities can be realized, then it is often preferable to treat the phenomenon as a "discretized" continuous field (Burrough & McDonnell, 1998). Typically, it is not possible or economically feasible to collect data points for every value within the area of interest. Therefore, an accurate continuous surface creation is an act of necessity for predicting these values. Some commercial GIS software introduces a set of spatial interpolation functions, allowing the user to generate results for areas of missing data. It also allows modeling within the software such as applying surface modeling techniques (ESRI, 2001). There are some types of spatial data that can be represented by surface such as elevation, contouring, constructing DEM or DTM or DSM, air temperature, air pollution, and even population. These types of data considered as continuous surface spatial data. When analyzing and modeling raster-based continuous data, it is noticeable that obtaining values for each cell is typically not practical and useful. Therefore, sample points are used to derive the intervening values using the interpolation technique within the modeling process. This set of sample points representing for example: changes in landscape, population, number of buildings per square kilometer in each neighborhood, or even the environment that can be used to visualize the continuity and variability of observed data across a surface through applying the interpolation techniques. These changes can be extrapolated across geographic space. By using SMT to model spatial data, the ability to create surfaces from sample data makes interpolation both powerful and useful. Additionally, SMT have the ability to describe solids through various boundary representation techniques. Boundaries may be constructed from simple geometric elements (primitives), facets – for example: triangular polygons (TIN) for vector – quadrilateral meshes, or function-based representation such as spline for raster (Fisher, 1993). Yet, even surfaces can be statistically distinguished as smooth or rough surfaces. As for the smooth surface, the surface can be demonstrated with little change in statistical information per unit distance such as topographic and climatic surfaces; in this case, it is called continuous. While, the rough surface is produced by rapidly or moderate changing values per unit distance because there is a major change in the statistical data with small changes of distance; and in this case, it is called discrete. In this research, the study deals with the regeneration of the raster rough surface modeling that have the structure of moderate discrete data such as urban growth expansion that extended in a statistical surface.

2.2 *Proposed SMT Approach in Urban Growth Application*:

In the literature, when using SMT approach to represent population-related with social indicators for example, researchers often manipulate population over space without covering the changes of population of specific local and small size zones. They focused on manipulating and analyzing population distribution. On the contrary and in our case, to accomplish a proposed raster surface model of time series urban growth expansion, analysts and programmers should deal with this growth as a raster moderate discrete feature. Cities transformed tremendously to be Megacities (Megalocities) that is considered as super-cities which contains a group of conurbations that are conjugated and formed a settlement community that has a population size more than ten million person in total (*i.e.* Greater Cairo Megacity with population number reached 13.5 mill. Person in the year of 2017). Moreover, Gigacities (Gigalopolis) which consists of a group of adjacent and contiguous Megalopolises, containing population size over 100 million person. This phenomenon starts to exist in the world especially in countries with large number of population size and expanding country area. For example: the eastern part of USA and the eastern part of china. Therefore, dealing with these expanding urban phenomena, should be examined and analyzed as a raster discrete surface. Figure 6 presents a proposed conceptual urban growth surface modeling approach for depicting and analyzing the urban growth development and expansion of both Megalopolitan and Gigalopolitan regions. To accomplish this modeling approach procedures, several conditions should be specified as follows:

2.2.1 *SMT Conditions*:

To use SMT for urban growth expansion through surface estimation, certain conditions should be set as follows:

i. The primary grid data input in this proposed modeling approach must be the derived land cover (LC) classification results from high or moderate spatial resolution satellite images. Prior processing procedures, the classification accuracy assessment of the resultant classified image should reached ($\geq$95%) of total overall accuracy.

ii. All SMT modeling procedures should be accomplished by grid/raster based data. However, if dealing with any discrete ancillary data input especially of LU/LC, data format should be changed. Changing the nature of data (such as: governmental land ownership, hazards, roads and other public utilities and etc.) from discrete data type to continuous by assigning a specific value for each pixel of the surface (arrays of points). In other words, operating the spatial analysis modeling by using discrete-to-continuous fields.

iii. Identifying and overlaying the census zone unit of the area under investigation as an ancillary vector data background in the final resultant urban growth gray level image to visually delineate the growth according to the country's administrative units.

iv. Checking statistics prior to reclassification process of the three resultant land cover classes -Growth obstacles, Urban area, and Non-urban area. It is an obligatory operation to avoid any noise cells and

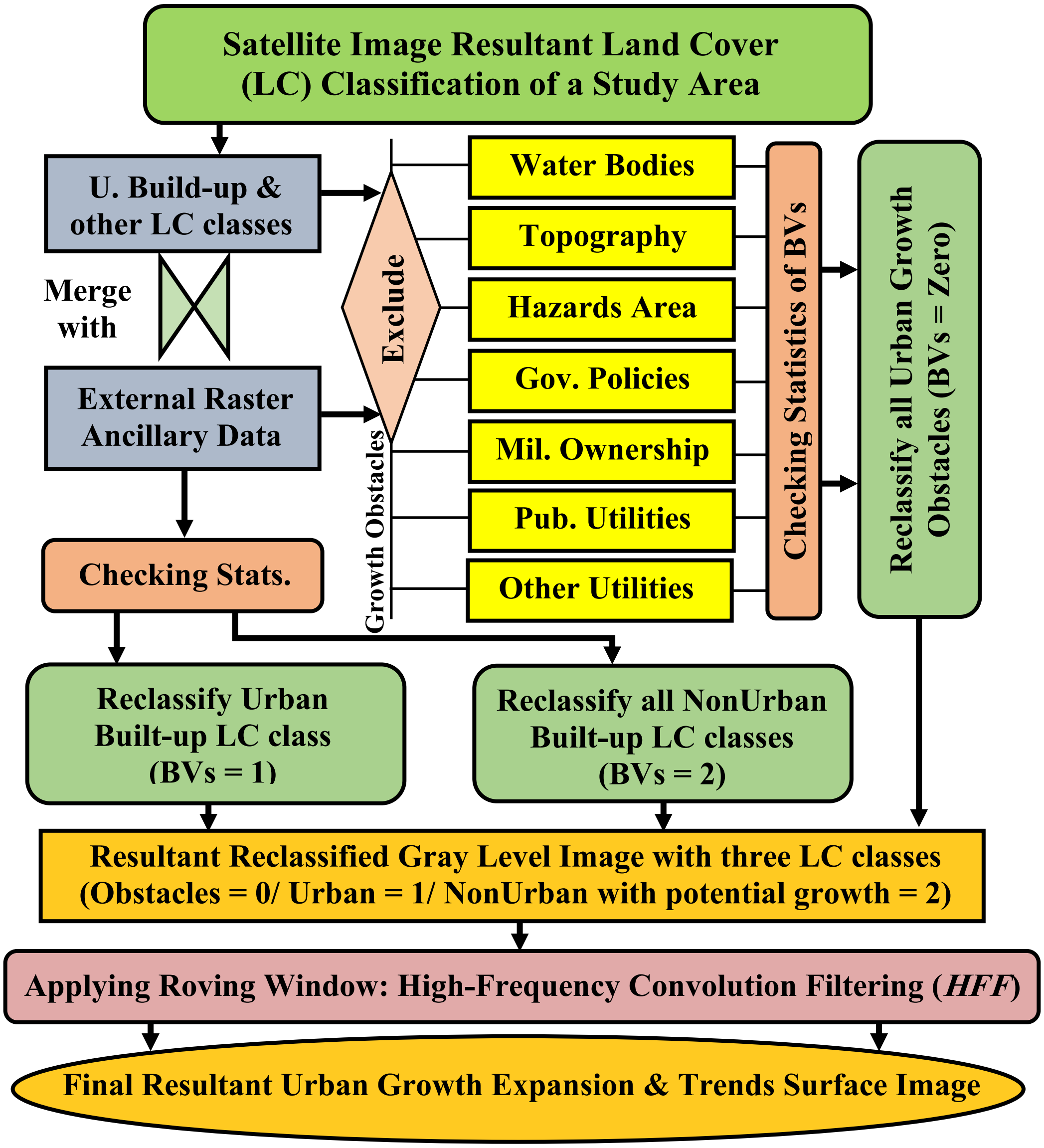


Figure 6. A proposed Conceptual Methodology of Surface Modeling Approach for Urban/Settlement Growth Trends and Possible Future Surface Expansion.

any occurring standardization errors that may appear according to the different source of data that is inputted in the modeling process.

v. When dealing with a temporal time series urban growth expansion of multi-time period, unifying resolutions (Radiometric, spectral, and spatial), projections, and datum of all different sources of data sets is an obligatory processing operation to permit an accurate comparison of the different coverages.

2.2.2 *Methodology Procedures*:

i. Identifying the research objective or the purpose beyond applying SMT is a preceding step in the proposed modeling approach. In other words, stating the research hypotheses and questions, *e.g.* picturing the current distribution, emphasizing potential future growth, and growth trends of the urban areas as major objectives need to be fulfilled and accomplished.

ii. Proceeding with defining and obtaining the remotely sensed data source. The modeling input data is the resultant output of the land cover (LC) classified image that it is preferable to be processed previously in a remote sensing software environment to ensure a very high accuracy verification result.

iii. Checking statistics process is a vital operation in the modeling procedures and it should be accomplished in several phases. The first statistics check is applied on the received input classified image to avoid any missing or changeable cells' brightness values (*BVs*) that may be appeared during the system format transferring process. The second phase, is checking all external raster ancillary data that is merged with the urban built-up area class and other pre-classified classes to assure that all data have the same spatial and radiometric resolution, projection, and datum. Prior to the reclassification process, final statistical checking process is essential to avoid any grid-cells with misleading and irregular brightness values such as noise.

iv. A reclassification process is required for all pre-classified land covers and other merged ancillary data. Three resultant classes should be designated and identified. These classes are as follows:

- The first class is the **Urban Growth Obstacles Area** class. It could be non-urban obstacles features such as: water bodies, topography, and others. Also, it may be some urban structure, such as individual roads and other utilities. Moreover, in the final processing result, it could be appeared as an already urban built-up area that is already fully occupied of buildings and also in the same time, it may be surrounded by other obstacles. This class type is given a new value of brightness values for all pixels in the class is equal to zero (BVs=zero).

- The second class is the existent **Urban Built-up Area**. It is reclassified to have the value of one to be substituted for all brightness values of original pre-classified class pixels (BVs=1).

- The third class is a **Non-urban Built-up Area** with a future potential growth. It consists of many vacant land areas that have no growth obstacles and may help for the future growth expansion of a city or any urban settlement community.

v. Generating a windowing functions High Frequency Convolution Filtering (*HFF*) on the resultant reclassified gray level image to change its spatial frequency characteristics. To perform the *HFF* function, a matrix of two-dimensional roving and moving window is processed. It is based on focal functions with a matrix (filter) contains a target central cell and surrounded by neighborhood cells. The size of the filter -the neighborhood convolution mask or usually called *kernel* (*n*)- is chosen to be 3×3 *kernel size*. It has the weighting value of (9) in the target central cell, and a weight of the value of (-1) for all the remaining surrounding grid cells. The *HFF* is designed to enhance the higher values and make it larger, while suppressing the lower values of each central cell. Figure 7 displays Three different scenarios of operating *HFF* on the central cells of the processed three resultant classes (the zero value indicates the growth obstacles class, the one value indicates the urban built-up, and the two value indicates the non-urban or non-built up area with no growth obstacles and have a future growth potential). When

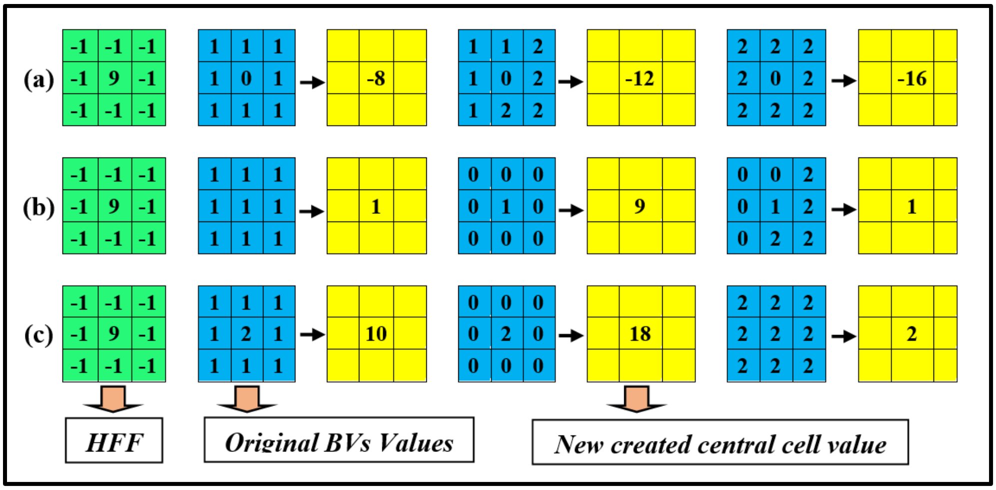
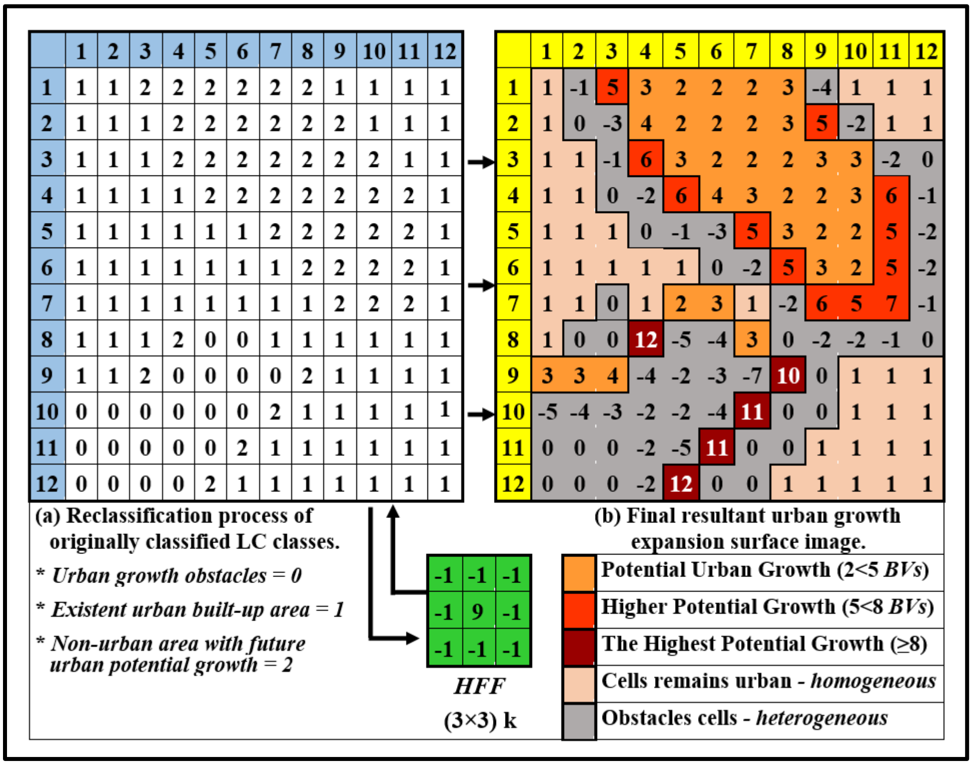


Figure 7. Operation of High-Frequency Convolution Filtering (*HFF*) on central cells of three different scenarios of each reclassified LC classes with kernel size (3×3): (a) central cell=0 / (b) central cell=1 / (c) central cell=2.

processing, the filter multiplies the correspond grid cell pair, then have the sum of all cells in the filter's window. Repeatedly, the filter keeps moving one grid cell to the right to calculate the entire grid coverage. Ending the process with specifying new values for each class. The central grid cell of the filter would take a gradually positive, negative, or zero numerical value in each window movement in the entire processed grid coverage. For the first class which was reclassified to the value of zero, the filtering results shows that all lower value became stable or lowest than before. Thus, the zero values became zero if the surrounding cells are all zeros, and suppressed to gradually minus numerical values in all other scenarios. Functionally, the second and third class that were previously reclassified to the values of 1 and 2, respectively, the filtering results shows that all resultant values were enhanced and enlarged to gradually positive numerical values in all other scenarios.

vi. Analyzing the final resultant output grid coverage is considered as the final modeling analytical procedure. Figure 8 displays the final result of the urban growth expansion & trends surface grid-coverage.



	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	2	2	2	2	2	2	1	1	1	1
2	1	1	1	2	2	2	2	2	2	1	1	1
3	1	1	1	2	2	2	2	2	2	2	1	1
4	1	1	1	1	2	2	2	2	2	2	2	1
5	1	1	1	1	1	1	2	2	2	2	2	1
6	1	1	1	1	1	1	1	2	2	2	2	1
7	1	1	1	1	1	1	1	1	2	2	2	1
8	1	1	1	2	0	0	1	1	1	1	1	1
9	1	1	2	0	0	0	0	2	1	1	1	1
10	0	0	0	0	0	0	2	1	1	1	1	1
11	0	0	0	0	0	2	1	1	1	1	1	1
12	0	0	0	0	2	1	1	1	1	1	1	1

	1	2	3	4	5	6	7	8	9	10	11	12
1	1	-1	5	3	2	2	2	3	-4	1	1	1
2	1	0	-3	4	2	2	2	3	5	-2	1	1
3	1	1	-1	6	3	2	2	2	3	3	-2	0
4	1	1	0	-2	6	4	3	2	2	3	6	-1
5	1	1	1	0	-1	-3	5	3	2	2	5	-2
6	1	1	1	1	1	0	-2	5	3	2	5	-2
7	1	1	0	1	2	3	1	-2	6	5	7	-1
8	1	0	0	12	-5	-4	3	0	-2	-2	-1	0
9	3	3	4	-4	-2	-3	-7	10	0	1	1	1
10	-5	-4	-3	-2	-2	-4	11	0	0	1	1	1
11	0	0	0	-2	-5	11	0	0	1	1	1	1
12	0	0	0	-2	12	0	0	1	1	1	1	1

Figure 8. Processing of applying *HFF* moving window on the first resultant reclassified LC classes to obtain the final resultant urban growth expansion & trends surface image.

The final output designates five resultant classes: potential urban growth that have a value range of (2 - <5 BVs), higher potential urban growth that have a value range of (5 - <8 BVs), the highest potential urban growth that have a value of (≥8 BVs), cells or pixels that was classified as urban built-up area and remains urban with no change after the analysis (these resultant cells is termed as a homogeneous class), and finally the growth obstacles class that have a value range of (zero - minus gradual numerical values). These resultant cells of the final class are termed as a heterogeneous class.

The proposed modeling approach gives a new methodological perspective to monitor and analyze settlement/urban growth in a GIS-raster surface based on satellite images and other merged ancillary data. Additionally, it offers a reasonable geospatial raster model to visually depict the urban/non-urban distribution and its future potential growth in a grid-based spectral space. Moreover, after producing the final result that displays the urban spatial distribution and potential growth expansion surface grid coverage with its five resultant classes, a vector overlay operation could be functioned. This vector overlay operation is for overlaying the governmental hierarchical administrative units to relate both present and future urban growth to these administrative units to enrich spatial relationships and the geospatial analysis procedures of this modeling regenerated approach.

3. Impedance Surface Modeling (ISM)

There are rarely any attempts were made by researchers to generate ISM techniques in settlement/urban growth applications. A wide range of scientific papers concentrate on developing this modeling technique on vector-based network analysis, while only few grid-based studies have used it in modeling oil or dense gaseous contaminant pathways over complex terrain, accessibility analysis, hydrologic modeling, or modeling shortest or least cost path for frictional surfaces. Hepner & Finco (1995) examines environmental problems associated with industrial development in proximity to the Mexico-U.S.A. border. They use GIS environment to analyze and integrate a wide range of physical, social, and ecosystem data related to increased industrial activities in border communities between the two countries. They delineate the atmospheric surface contaminant migration pathways from primary industrial sites for dense gas contaminants. Distance buffer and impedance surface approaches are used to delineate and model surface pathways. Their output result of these models is used to assess the potential risk to human residents. Grossardt *et al*. (2001) present the analytic minimum impedance surface (AMIS) methodology and evaluate its application in their study area in the southeastern U.S.A. They generate a continuous geographic surface that summarized scores pertaining to routing preferences and obstacles. Liu & Zhu (2004) integrate GIS tools such as "accessibility analyst" built as an extension to the GIS software package, with an accessibility analysis in urban transportation planning. They incorporate a number of accessibility measures in their analysis ranging from catchment profile analysis to several travel-impedance measurements for estimating the travel distance, time, or cost. They recommend that their methodology can be applied to a wide range of issues in urban transportation planning, such as for studies on the relationship between transportation and land use, evaluation of transportation network efficiency, and transportation infrastructure planning. Udoh (2010), evaluates oil spill hazard using spatial analysis modeling techniques in South Eastern Nigeria. He uses hazard sources and impedance surfaces as two main components in his paper. He established a hazard surface to reflect the movement of oil over each impedance surface. In this model, high hazard zone has a cell value over 60%, while the moderate and marginal zone constitutes less than 40%. Tang & Dou (2023) operate a computation experimental study of a multi-resolution raster-based cost surface model to calculate and examine the Multi-Scale Least-Cost Path (MS-LCP) to enhance computational performance for large-scale grids for the purpose of determining the most cost-effective path. For all research experiments, a Java programming language is employed and infused in a GIS software environment. Their experimental results on synthetic and real data demonstrate the effectiveness of their proposed method. Moreover, they conclude that the efficiency of the method on large-scale data can be significantly improved through parallel computing. They addressed their research to the fields of geography and GIScience and recommend that their proposed method can be expanded to serve broader purposes.

3.1 *Understanding Impedance Surface Modeling Approach (ISM)*:

Impedance surfaces or friction surfaces are considered as obstacle areas that slow or impede progress, either because the intervening terrain is too rough, or because fences surround the intervening land topography (DeMers, 2008). These obstructions or difficult terrain will often reduce the movement ability. There are two types of barriers and friction surfaces: absolute and relative barriers. The absolute barriers prevent movement completely through them, such as: (steep mountains, cliffs, deep water bodies, and etc.). While relative barriers are also friction surfaces but at discrete locations that have slow movement possibilities.

It acts to impede movement and incur a weight or cost for this movement across these barriers, such as: (moderate hilly terrain, shallow water bodies, and etc.).

Impedance Surface Modeling (ISM) can be applied in both vector and raster data models. In vector-based analysis the ISM, is a measure of the amount of resistance, or cost, required to traverse a path in a network, or to move from one element in the network to another. Resistance may be a measure of travel distance, time, speed of travel multiplied by distance, and so on. Higher impedance values indicate more resistance to movement, and a value of zero indicates no resistance. An optimum path in a network is the path of lowest impedance, also called the least-cost path (GIS Dictionary, ESRI support center www.esri.com). Same concept can be identified for raster or grid-based analysis. Impedance surfaces are also raster data sets in which the value in each cell represents the difficulty of movement over that cell. By using a distance-weighted average between cells, unique impedance can be calculated for each link between adjacent center points in the network. Also, by summing impedances between adjacent cells, it would be easy to calculate the overall impedance between any two cells. Raster modeling of barriers and friction surfaces is conceptually fairly simple. By using the impedance value, the user specified numerical value used to simulate the effects of barriers or friction surfaces. It is also employed in the same way for network modeling, where the impedance values indicate the degree to which a network allows travel.

3.2 *Proposed ISM Approach in Urban Growth Application:*

Conceptually, when reviewing the scientific literature, the grid-based ISM approach deals with identifying the least amount of effort that would be taken to delineate the best possible path. Indicating frictions or impedance factors and their specified weights are considered as key elements in this approach. From this prism, we could use this idea to indicate the current movement of urban growth on one hand and allows the prediction of its future movement trends on the other hand. Therefore, several procedures are suggested to be taken before applying

ISM as a preprocessing analysis by identifying the ISM involving factors and depicting its methodology.

3.2.1 *Basic Concepts and Definitions*:

In the raster environment, there are basic concepts and definitions of both conventional and proposed ISM approach should be identified as follows:

(a) Classified urban growth impedance factors:

It is the starting analytical procedure in the proposed modeling process. It consists of several classified grid-layers of human and physical impedance factors. Each layer is classified into a number of classes. Additionally, an existing coverage of settlement/urban built-up area land cover class should be included in the human impedance factor layers.

(b) Reclassification of classified impedance factors:

It is a process to reclassify all previously mentioned urban growth impedance factors to allow and ease the comparative processing among all grid-layers in the proposed model. A common scale of a range of numerical values should be practiced in the classes of all layers. The pre-classified values of classes is transformed to a range of positive absolute numerical values (from one to 10) to delineate a common measurable scale of all presented layers. All layers are performed in friction surfaces.

(c) Friction surfaces and types of barriers:

Conventionally, friction surfaces are conceptually designed as matrices (grid-based surface) of impedances or obstacles that contain no cumulative values, but adding instead many moving resistances within the whole grid-surface. In other words, friction surfaces are crucially considered as a significant factor in developing and producing more realistic accumulated surfaces. Similarly, as accumulated surfaces, friction surfaces can be performed in either isotropic or anisotropic friction surfaces. DeMers (2008), defines the isotropic surface as a completely uniform surface in all directions around a starting central cell. He explains that this surface type can be performed in raster environment as a series of concentric rings, one grid cell in diameter, around the starting grid cell. He also terms it as a "simple surface" and it can be processed and displayed in three dimensions just as well. Additionally, as for the anisotropic friction surface, it was termed as a "functional surface" that is act as the opposite of the previously mentioned type of surface. This anisotropic surface is created by measuring cell zonal distances that have all directions differ in diameters from the starting cell; producing rings that are not uniform in all directions and the starting cell is not necessarily to be located at the center. Furthermore, different friction or barrier layers can be combined into one to perform an anisotropic type of modeling with obstacles values are not equal on axes of all directions. It can be named as raster-based "Growth Impedance Layer".

(d) Impedance weights:

Identifying impedance weights for each friction phenomenon is the corner stone of this proposed modeling approach. To compute these weights, it differs in estimation from one analyst to another according to the degree of the severity of physical or human frictions from his point of view (in other words, it is an "Analyst-Defined" decision. In this case, the researcher should define all frictions that would be operated in the modeling process. The degree of the severity of friction surface is measured by percentage. Suppose, for example, that we have two specified friction or impedance surfaces (two grid-layers of impedance factor), it would be both summed together to have a percentage of 100% of total frictions. However, one factor may be impeded more than the other. For instance, avoiding steep slopes factor may be much more important and have a greater friction value than the land use or the public utilities factors. In this case, the analyst may give an impedance weight influence (impedance or friction weight percentage or ratio values) of 70% (or 0.70) and of 30% (or 0.30), respectively; (both factors together complete 100% {percentage form} or 1 {friction or ratio form}). This influence percentage of factors is an "*Analyst-Defined*" that may be varied from one analyst to another depending on the spatial variability of the selected study area, its changeable landscape and topography, and the researcher's own estimation perceptive.

(e) Accumulated surfaces:

Conventionally, accumulated surfaces are conceptually considered as raster models that calculate the least obstacles path from a grid-cell to another (from a start-pixel to a target-pixel). It is like traveling through the cells across the grid's spectral space. It is termed as accumulated surfaces, because it refers to the process of calculating the incremental values of grid cells. In other words, it implies that there is an amassing or increasing of values from the path that connect the start cell (origin) with the target cell (final destination). For example, if we have a row of cells in an accumulated surface and if we move across four cells in the row where the first two cells each has the value of two (2) and the second two cells each has a value of one (1), as a result the accumulated value (sometimes called "cost to travel through grid-cells) through the four mentioned cells is the value of six (6); this value is stored in the start cell. The accumulated surfaces can be performed in either isotropic or anisotropic accumulation surfaces. The isotropic type of modeling has same or identical values along axes in all directions, while the anisotropic type of surface modeling is considered as the opposite of the first type, where the cost values are not equal on axes of all directions.

(f) processing pixels' patterns:

There are three main types of pixels' patterns. Figure 9 illustrates an orthogonal, diagonal, and convolution pattern that are usually used in the modeling processing. On one hand, the orthogonal pattern focuses on computing only the direct orthogonal cells (cross shape) around the central pixel, and it does not examine the missing diagonal cells' values during accumulation calculation process on the other hand. While the diagonal pattern focuses on computing only the diagonal cells and ignoring the orthogonal neighborhood cells. As for the convolution pattern, it examines all neighborhood cells around the central pixel. This convolution pattern considers functioning the nearest eight convoluted neighboring cells (orthogonal and diagonal), and may also functioned 16 convoluted neighboring cells in some other applications. Therefore, the convolution pattern of eight neighboring cells is the best pattern to be chosen and applied in the proposed Impedance Surface Modeling Approach.

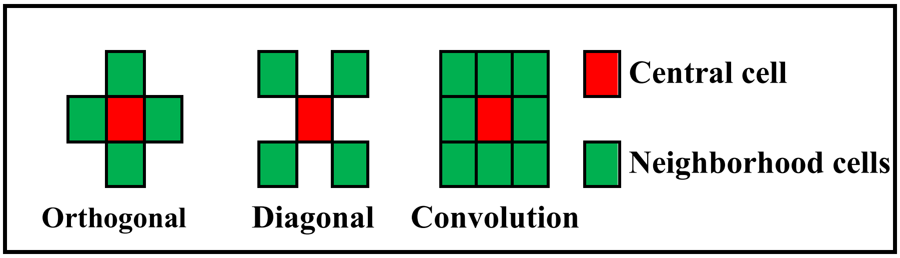


Figure 9. Three main patterns of processing raster cells in ISM approach.

(g) Identifying starting and ending processing cell corners:

Unlike the traditional impedance surface modeling that calculate the least-cost path -for movement from a starting grid cell to an ending grid cell location, forming a linear routing shape according to either compute a simple or a functional distance-, the proposed modified model works on the entire raster surface not only to find the shortest paths and least cost linear routes, but to depict the best ways to propose an urban growth surface. The result should be an entire cumulative surface that should avoid impedances and frictions that have the highest cost (means highest values), which impede the growth expansion either partly or completely. Moreover, the least cost (means lower values) in this case indicates the possible urban growth movement across the continuous raster surface. Two main factors control the rightful choice of the starting and ending computation cells. The first is: the starting cell should have processed and reassigned at column zero, row zero -in other words, assigning a new origin point of the starting cell-. The second is: the ending computation cell would also control assigning the processing movement direction. Figure 10 depicts and displays the reassigning process of staring cell as a new origin cell (col.=0, r.=0) and the movement direction according to the specified ending cell. In this case, it is measured by degrees, *i.e.* the direction from source to target cell is North West=315º.

3.2.2 *Identifying involving factors*:

Despite the fact that ISM approach is rarely used in urban growth application, a proposed modified approach can be generated to reach this goal. Depending on identifying the factors' values that would be used as impedance values, a delineation of the movement of the urban growth trends could be easily generated. Certain conditions should be specified before processing the ISM approach, such as: unifying the data source

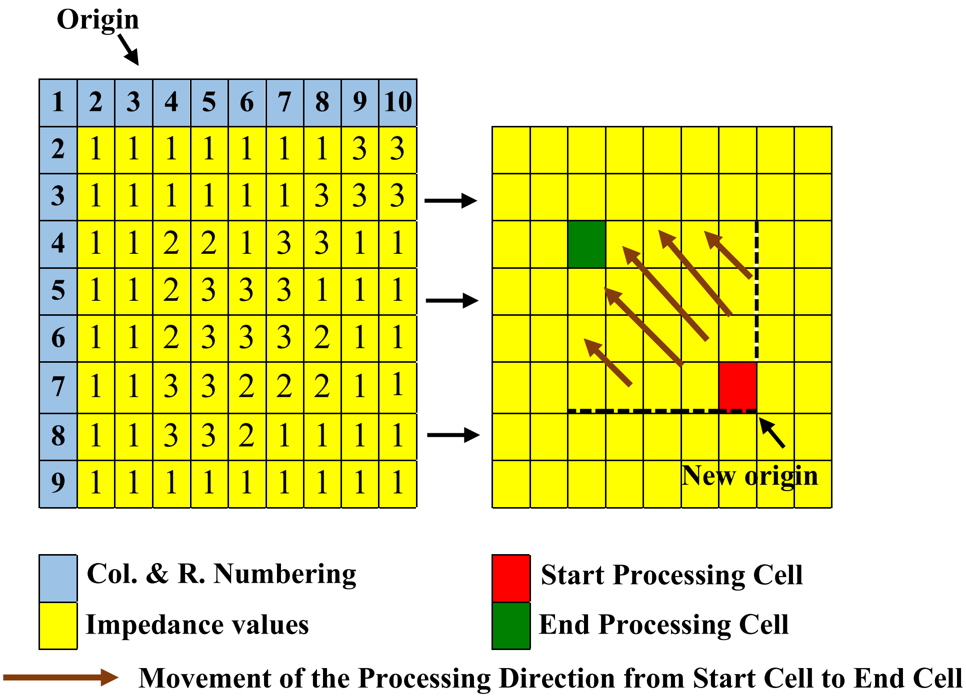


Figure 10. Reassigning a New Origin Cell according to specify the Start and End Processing Cells of the Proposed ISM algorithm.

of all raster coverage data sets, unifying grid cell resolutions such as radiometric (storage capacity), spectral, and spatial (cell size) of all used data sets, and identifying the movement processing direction of the cells in the ISM algorithm. To identify the significant factors; which contribute to the impedance and to develop the functional dependence between those factors and the impedance variables, major procedures in the impedance surface modeling are applied. These factors defer from one case study to another. As it was mentioned above, the concept of assigning friction and impedance values is simple and is easy to be identified, whereas operationally, it can cause some technical difficulties. In the case of identifying urban growth expansion, researchers have to know and specify the impedance that the land cover can cause to urban growth as it moves through it and also identifying the impedance factors that implicitly effects the urban growth in the study area. Figure 11 displays the proposed selected physical and human impedance factors that act as urban growth obstructions. These factors are: topographic obstacles, steep slopes, deep water bodies, agricultural

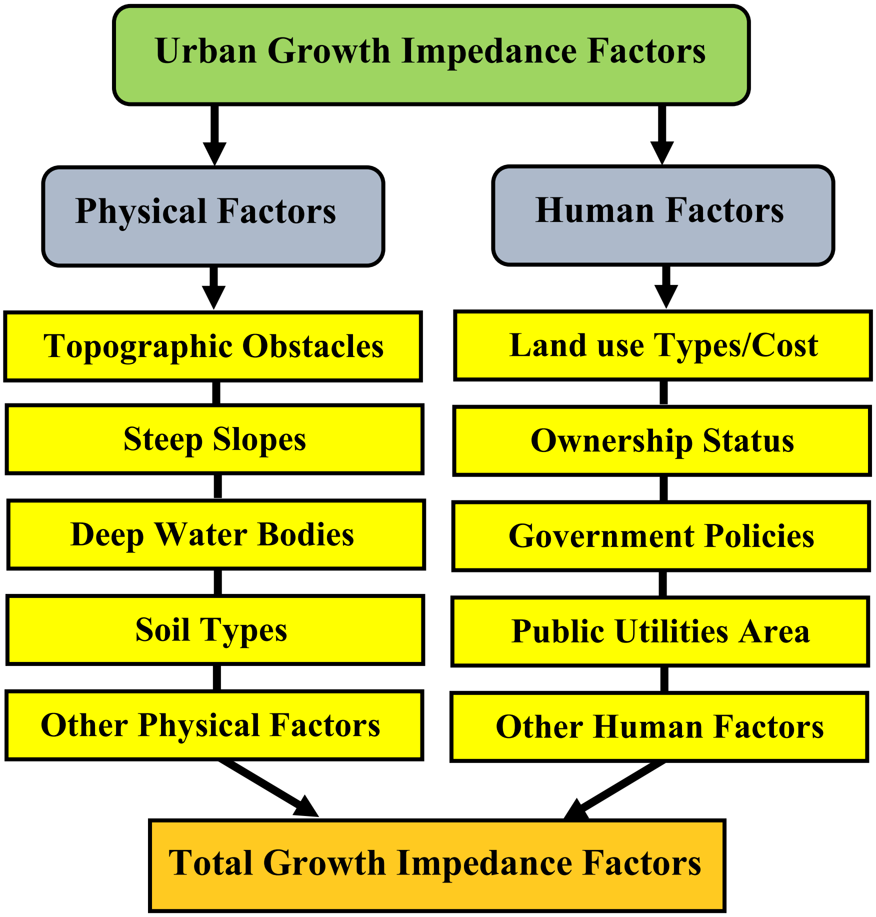


Figure 11. The proposed Urban Growth Obstruction Factors of Impedance Surface Modeling Approach: physical and human impedance factors.

lands, soil types, land cost, ownership status *i.e.* military or governmental ownership, governmental policies, public utilities, and certain land use types. Notably, these factors along with other factors that differ from one country to another are considered in real world as the impedance – barriers and friction – surface that obstruct and even prevent the expansion of urban growth.

3.2.3 *Proposed ISM Methodology Procedures*:

Figure 12 presents a suggested conceptual methodology of ISM approach that detect, depict, and analyze current movement of urban growth trends based on the existed impedance surfaces according to its

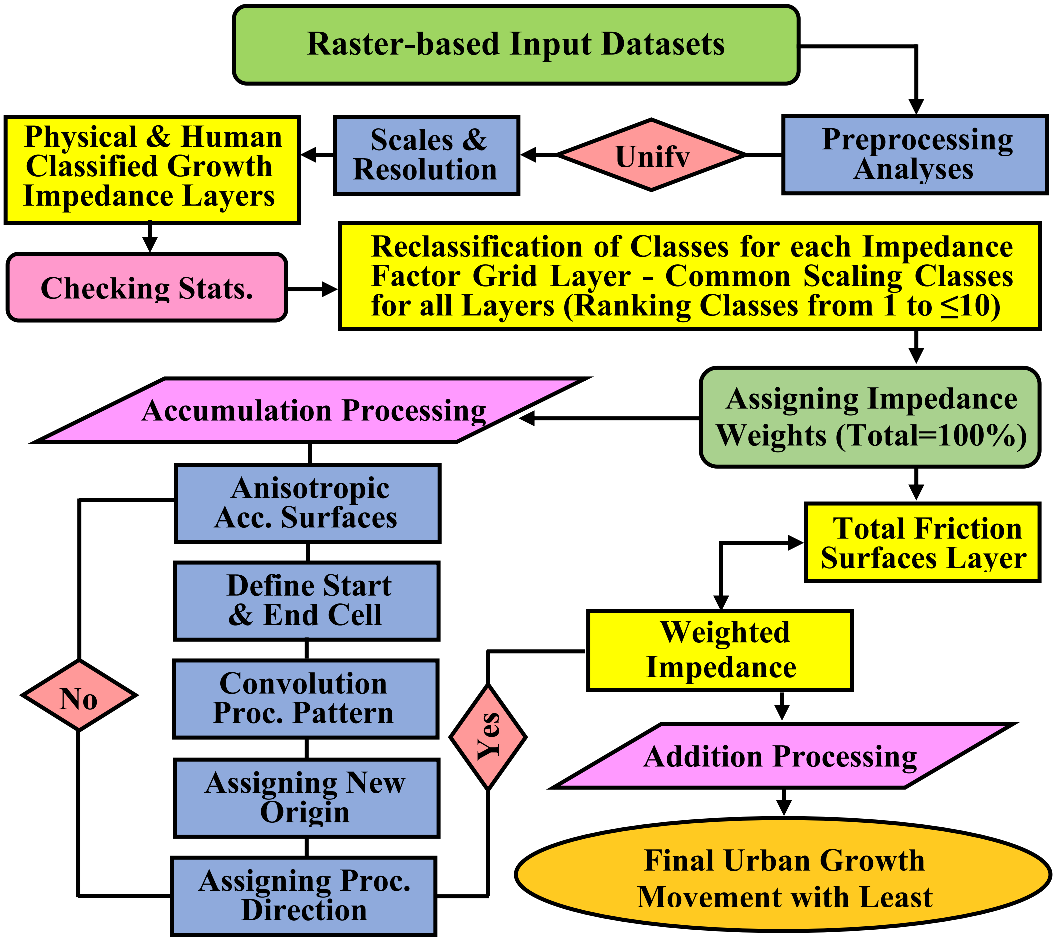


Figure 12. A proposed Conceptual Methodology of ISM Approach for Possible Future Urban/Settlement Growth Movement with Least Impedance Surface.

spatial or geographical growth resistance sites in the spectral surface. It allows not only the prediction of future growth movement trends, but also its future development and expansion. The procedures are as follows:

i. Preparing the input coverages of the raster-based dataset different sources. This data is ranging from ordinary satellite images that "may have" or "may have not" the same temporal, spectral, spatial, and radiometric resolution. Moreover, other different raster datasets sources can be used for the proposed model processing.

ii. In case of different data sources that have scales and resolutions, preprocessing analyses are required to unify all resolutions in all the grid-based datasets. For example: if the raster datasets have different spatial resolution, a resampling process is required prior to analysis. Nearest neighbor assignment technique is recommended to determine the location of the closest cell center on the input raster and assign the value of that cell to the cell on the output raster. The purpose of using this resample technique is to maintain the original cell values from the input raster dataset without changing it into new values, which will give a better result later in the processing analysis. Consequently, during the accumulated-weighted impedance processes, the resultant output multiple raster datasets have the same cell spatial resolution. This act is also required for unifying all other types of scales and resolutions (spectral and radiometric), scales, projections, and datums.

iii. Preparing and identifying physical and human impedance raster multi-coverage as a single grid layer for each factor. A classification process should be accomplished for each impedance factor layer. In addition, a checking statistics procedure is examined for all grid layers to avoid any positional error that may appear between layers in a latter modeling procedure.

iv. Reclassifying the previously classified impedance datasets to a common scale. Each impedance factor is reclassified to a number of classes on a scale from one to ten ($1 \leq 10$). The attribute of each dataset should be examined to determine their contribution to the growth impedance or to the urban growth obstacles (degree of influence). This process is applied only on the classified classes of each impedance factor layer independently (class-based for each layer). For example: it is obstructed to build over the steep slopes, thus this class in the slope layer is assigned an impedance value=2. Moreover, the steeper slopes class in the same layer is assigned a higher impedance value, while the most steepest slopes class is assigned the highest value (impedance value=6) according to the determined and estimated scale by the analyst himself (Figure 13a). This procedure is repeated for other produced impedance factor layers according to its obstruction degree of influence and also according to the user's own evaluation and perspective. Finally, the processing output result is displayed as a set of reclassified impedance surface multi-layers.

v. To produce the final output layers of impedance surface (friction surface), a new reclassification weighted processing is computed. This process is applied on the whole resultant reclassified impedance surface multi-layers that were produced from the previous processing step. All impedance layers are assigned a total percentage of influence (total obstructions) of 100%. Each impedance layer is evaluated on a weighted scale, which is ranging from "greater than zero" to "less than or equal one" ($> 0 \leq 1$). Unlike the previous step, the assigning process of the impedance weights is applied for each "urban growth impedance factor" layer independently according to the selected impedance weight of this layer (layer-based of total layers). When finishing processing all layers, the total impedance weights of all layers together must be equal to the value of 1 or to the percentage of 100%. A total friction surfaces one layer is produced.

vi. To prepare the accumulation processing procedures, certain functional acts should be accomplished. Firstly, selecting an anisotropic surface as a functional surface type is essential for this proposed urban growth modeling algorithm. Secondly, a convolution pixel pattern is chosen to process all eight nearest neighboring cells. Thirdly, identifying the starting and ending processing cell for the growth movement processing analysis. This follows by assigning a new origin computation cell and delineate the processing movement direction. Thus, if all the above mentioned procedures are successfully functioned, weighted impedance layers are produced by dual functioning with the previously resultant "total friction surface" layer.

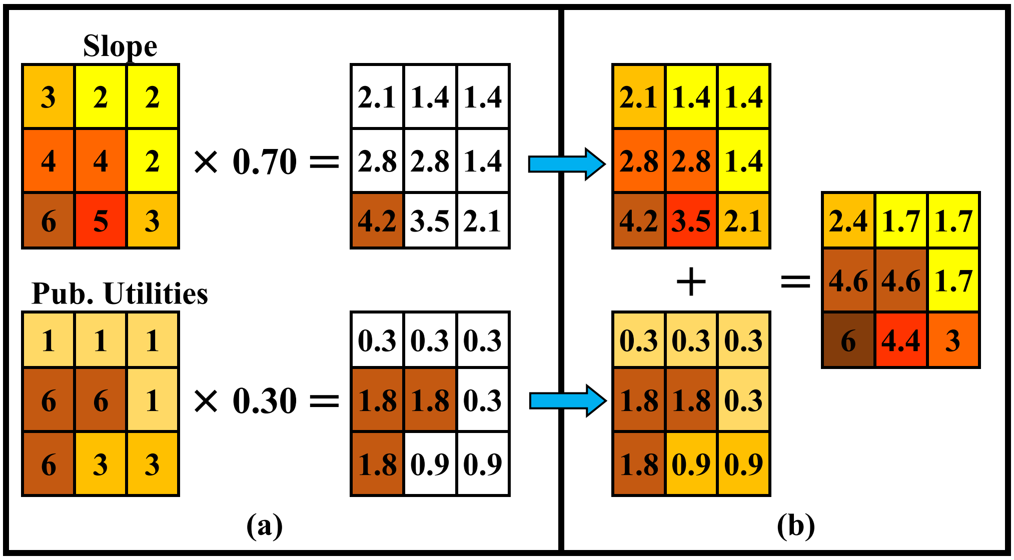


Figure 13: Producing the Total Weighted Impedance Surface Layer (a) Estimating the Impedance Weights of Pre-Classified Friction Factors according to the Analyst-Defined Influence "Ratio" or "Percentage" of Impedance. (b) Multi-Layers Mathematical Addition Process of Overlay Analysis to Produce a Final Resultant Accumulated Layer.

vii. Notably, that the procedure of computing the impedance weights in an accumulated surface of each layer is applied according to the delineation of the percentage of obstruction influence, which is also estimated by the analyst himself. In this step, the researcher has to define the importance of impedance delineated factors to be gradually avoided by the urban growth expansion. Although the reclassified classes share the same scale of impedance value, the weighted classes are different from one class to another according to the pre-delineated percentage of obstruction influence. For example, in figure 13a, the cells that have impedance (friction) values equal to six in both slope and public utilities coverages, differ in their resultant weighted influence percentage of impedance to have different values of 4.2 and 1.8, respectively.

viii. Applying a mathematical overlay analysis to join the resultant weighted impedance of all grid-based multi-layers together in one single layer by applying a raster mathematical addition processing of all previously resultant weighted multi-layers in a GIS software environment (Figure 13b). A single line expression in raster calculator can be operated. Multi-line expressions can be also executed to generate some complex functions, such as calculating the impedance surface, then creating impedance-weighted grid cells, and then applying the addition process; all can be done as one process in raster calculator. The final overlay output of overall joined or combined weighted-impedance raster is the result of adding together the weighted percentage of influence of all raster weighted impedance layers. Therefore, the final result of this process is an accumulated total weighted impedance surface layer.

ix. Back to the step of stating a condition of assigning the cell movement and direction from one source cell (Start Processing Cell) -that is reassigned earlier by a value of zero- toward a destination target cell (End Processing Cell), the identification of this cell movement is crucial to show which direction that this cell will prefer to follow within several paths. This movement preference is conditioned by having the least impedance values. As a processing result, this will show the possibility of having a future urban growth expansion. In this context, an integrated programming algorithm environment can be used to generate the zonal distance of the cell movement and specifying the least impedance proposed growth classes. A simple *Macro Programming Algorithm* can be developed by operating either a "commercially-independent" or a "GIS-Built-in" programming language software. To generate this algorithm, three main objectives must be achieved. The first objective is to specify a direction coding or specifying the movement destination from the source (start) to target (end) processing raster cell, and may directed in all possible directions in a range of (0º-360º) clockwise rotation degrees according to the existing direction between the two cells (Figure 14a). For example: by following the eight clockwise (cardinal and ordinal) geographical directions, it is starting from N=0º, NE=45º, E=90º, SE=135º, S=180º, SW=225º, W=270º, NW=315º, and ending of N=360º. While the second objective is to

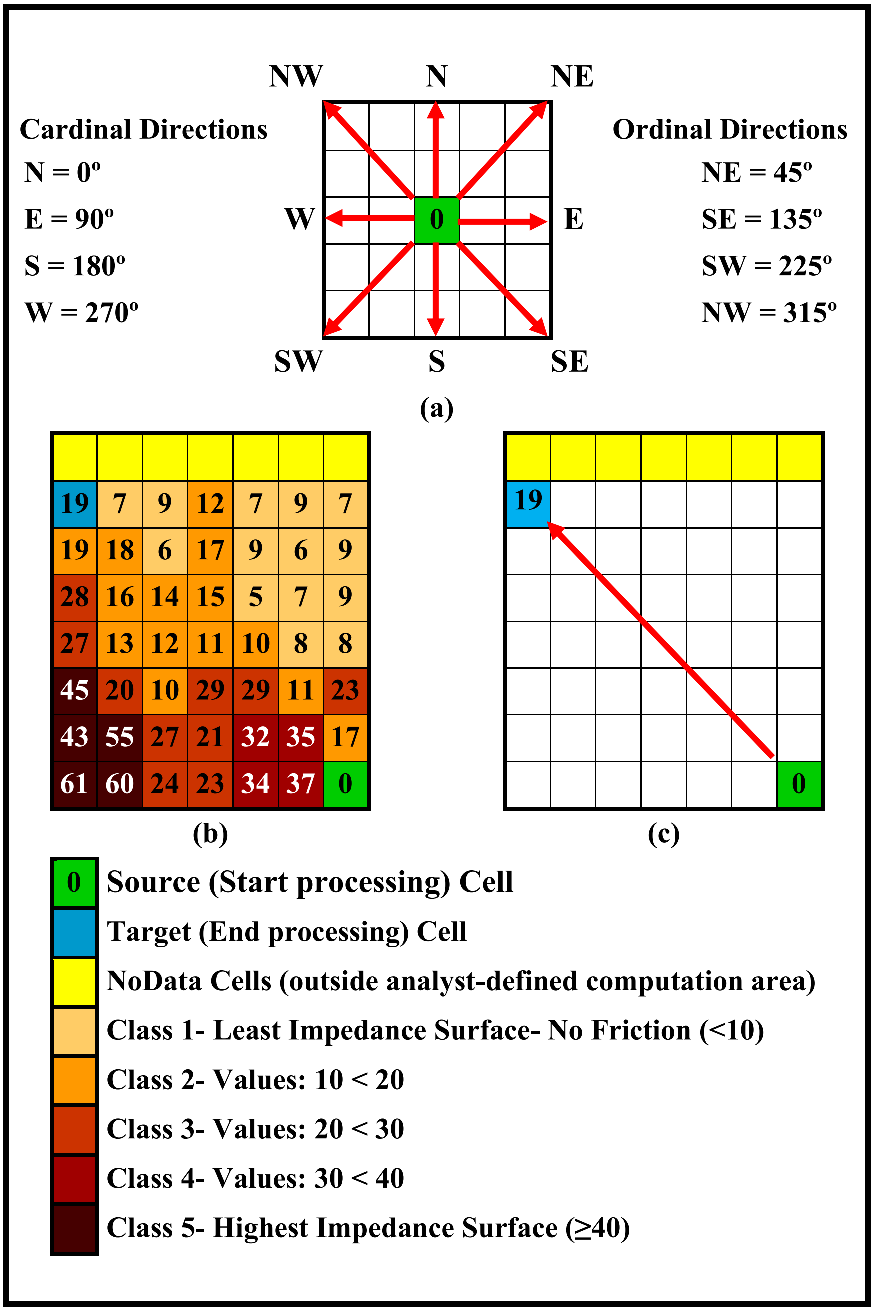


Figure 14: Producing the Final Proposed Urban Growth Movement within the Resultant Impedance Surface Classes. (a) Specifying Direction Coding. (b) Computing Manhattan Distance according to Direction and Parameter. (c) Generating Final Impedance Classes: Class 1=the best suitable urban growth allocation with no friction, while class 5=the highest friction surface that completely disallows urban growth.

specify the value of maximum distance, processing direction, and parameter of pixels' surface to be operated in a way that any cell exists outside this specified distance will not be considered in the computation process and will be given the value of "NoData" (cells that fallen outside the specified distance coded "No Data Cells" and have no cell values). Otherwise, the algorithm will be operated for the whole raster coverage without stopping and in this case, the NoData value would not be existed. For this reason, a "Manhattan distance" is selected to be operated in the proposed modeling approach to regulate the movement between the two cells (source and target) where it can move easily in a grid surface to avoid having a "NoData" cell inside the analyst-defined parameter of the processing grid surface that is created according to the defined maximum distance and direction code (Figure 14b). Whereas, cells that exist outside the analyst-defined maximum distance and resultant parameter is excluded from the processing and assigned no value cells in the output resultant grid layer. The Manhattan distance equation between the two start and end processing cells is as follows:

$$\textbf{Manhattan distance } (d) = (x_1 - x_2) + (y_1 - y_2)$$

Where (x_1, y_1) is the Cartesian Coordinate of the start cell, while (x_2, y_2) is the Cartesian Coordinate of the end cell. As for the third objective, identifying the number of desired classes is also an analyst-defined decision. It is allowing the analyst to specify a number of impedance classes that ranging from the least to the highest impedance surface. In our case, five gradually classified impedance classes are created; such as follows: least, median, high, higher, and highest impedance (friction) surface classes (Figure 14c). In one hand, class (1) is depict the least impedance surface that offers the best suitable location in the entire geographical surface for urban growth without any frictions, while on the other hand, class (5) has the highest impedance or friction accumulated values that disallow and forbid any urban growth in the grid surface. Noticeably, the highest possibility of urban growth expansion class has the least accumulated weighted impedance surface values in the raster data output, while the lowest possibility (impossibility) of urban growth expansion has the highest accumulated weighted impedance surface values and assigned as areas with the highest friction that forbid any growth.

The result of using this proposed modeling approach is giving a reasonable good estimation of future trend of urban growth. The idea of calculating all impedance for the entire study area surface finds suitable locations for new sites, by creating an output resultant grid that meets all conditions specified in the algorithm. Moreover, the proposed (ISM) provides a good tool for urban planners to monitor the future urban growth change and expansion. In addition, it provides a good estimation about the size of this expansion by measuring the accumulated weighted impedance surface and distance. The only weakness of this modeling technique is that it may differs in accuracy and results according to the researchers' scientific capabilities. Like all previously examined and modified GIS grid-based geospatial modeling, this approach depends on the analyst himself to define most decision rules and parameters in the processing procedures. If not follows the proposed methodological procedures precisely, there are no limitation for ending the operational process. Supposing -for example in this case; if the processing maximum distance, direction, and surface parameter decision rules coding are not specified or ignored by the analyst, the process will continue computing with assigning and clustering the impedance surface classes without stopping until it finishes and completes the entire raster-grid layer. Moreover, the higher scientific skills of applicant researchers, the higher accuracy and the final resultant grid-layer of urban growth movement with least impedance surfaces are significantly produced. Finally, in addition of expending a lot of time in modeling processing and consuming a huge machine storage space, it also does not reflect or intelligently recognize the real world case of the natural limitation and flexibility of urban growth dynamics.

VI. Discussion and Conclusion

This research study dealt with a thorny topic that is experienced and contradicted among the Egyptian geographical community and some other countries. It focused on dealing with the modeling procedures and the different algorithmic models within the environment of the Geographical Information Systems. Although the research was interested in studying and modifying some selected GIS geospatial grid-based modeling algorithms, it was initiated by correcting all the misconceptions that are circulating among researchers about the GIS modeling types and categories. The major scientific confusion between the ready-to-use geospatial models that are built within the GIS software environment, the created modified geospatial models that are either compatible with the system or be completely programmatically independent, and the programming-based created models from scratch. Moreover, it shaded lights on the difference between the Spatial/ Geospatial models of a GISystems, and the Geo-Artificial Intelligence models of a GIScience. Followed the differentiating between systems and science, is to differentiate between the entitled terms of GIS-analyst and GIS-modeler. As for the analyst, he uses the ready-to-use geospatial type of modeling that built within the GIS software. The only difference between one analyst to another is the choices alternation and different arrangements of input elements, parameters, and layers to be infused in the model, which are differ from one research to another according to the purpose of the study. While, the modeler created individually an independent algorithmic model that is produced by operating a computer programming language. This created model is compatible with or completely independent from the GIS system environment. Accordingly, this created modeling algorithm is named after, documented, and attributed to its original creator. Therefore, this research study contributed to correct these misconceptions about modeling and presented an attempt to clarify the difference between their types. From this standpoint, the researcher chose three grid-based geospatial modeling algorithms to be enlighten. These algorithms are: Cartographic Modeling, Surface Modeling Technique, and Impedance Surface Modeling. The research was not limited to study and interpret these three models only, but rather it presented a new perspective for these models, with regard to radical structural modifications that were proposed. These modifications are made to change the design and programming construction of these algorithms so that they are consistent with the applied and experimental aspect that was selected in this study, which is modeling settlement/urban growth change. Moreover, the suggested modifications are operated despite the fact that the original created programming bases of some of these algorithms were originally designed to be applied to other geographical, planning, and spatial phenomena. However, the proposed modifications of all selected geospatial algorithms were designed to repair their original deficiencies as well as regenerated, redesigned and rebuilt these algorithms to conduct and operate the specific chosen research application. The final research modifications showed and confirmed promising resultant outcomes, which greatly benefited the chosen application in terms of overcoming some programming shortages that were already existed in the traditional algorithmic models, such as: limitations of applied practical modeling usage, locality, as well as shortcomings in algorithmic performance.

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