Simulation of urban sprawl and the analysis of the sustainability of developments using Cellular Automata and Remote-Sensing: Findings from Kurunegala, Sri Lanka

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Abstract

Cellular Automata (CA) models are effective methods for simulating land use change. This research used CA to model the pattern of urban sprawl in the Kurunegala district in Sri Lanka, within the period from 2022 to 2027. The model was developed using land use land cover (LULC) data ranging from 2007 to 2022. Urban sprawl prediction models are extensively used in contemporary studies, with the majority of models emphasizing the technical components of modeling. However, most of these models do not assess their simulated results against the real development potential or any suggested development potential. The objective of this research is to simulate the urban sprawl in Kurunegala and compare the results with the assessment of development suitability, which will also be carried out using the zone factors assigned in the Urban Development Plans prepared by the UDA (Urban Development Authority) Kurunegala. According to the modeling findings, urban growth in Kurunegala will spread out during the next five years, covering an approximate area of 309.534 square kilometers by 2027. The simulation showed that the distribution of urban sprawl aligns with the suitability of the region for development, as established by the study done using the Arc Map model builder. Nevertheless, the forecast for the zone factor in 2030 does not completely align with the predicted outcomes.

Keywords: Cellular Automata, Modeling, Urban Sprawl, Suitability, Development Potential.

1. Introduction

Urbanization is a widespread phenomenon with significant impacts on land use structures, the preservation of the environment, and social and economic growth. Understanding the evolving patterns of urban growth and their impact on both the constructed and natural surroundings becomes more crucial as urbanization persists (Mosammam et al., 2017). Using Cellular Automata (CA) models in conjunction with remote sensing data is an efficient method for simulating and analyzing land use change, which includes urban expansion (Tripathy & Kumar, 2019).

This research seeks to employ CA modeling approaches and remote sensing analysis to assess the appropriateness of the suggested zone factors by the UDA development plan for growth in the Kurunegala Municipal Council area. Several studies have been conducted on urban expansion, a complex phenomenon influenced by variables such as growing populations, growing economies, and land use policies (Surya, 2016; Silveira et al., 2021; Zhang & Su, 2016). Multiple studies have emphasized the detrimental effects of urban development on natural ecosystems, such as decreased biodiversity, fragmentation of habitats, and increased emissions of carbon dioxide (Mustafa et al., 2018; Charif et al.,...

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DOI: https://doi.org/10.4038/bhumi.v11i1.100
These results highlight the vital need for environmentally friendly urban planning and administration to reduce the adverse consequences of urban sprawl (Deep & Saklani, 2014; Navid & Aghababa, 2013; Kumar et al., 2016). Existing geospatial-based urban growth models are mostly dominated by the CA models such as the CA-Markov chain models, and CA-Logistic regression-based models (Navid & Aghababa, 2013). CA modeling has established itself as a potent instrument in urban studies (Xing et al., 2020), allowing for the simulation of spatial transition as well as urban development (Yang et al., 2020). By depicting small land parcels as cells and implementing transitional rules determined by neighboring cell characteristics, these models can replicate the spatial dynamics of urbanization. Some studies use CA models to effectively simulate urban development and investigate various urban planning scenarios (Chakraborty et al., 2022; Li & Gong, 2018; Santé et al., 2010). The objective of this study is to provide useful insights into the urban development processes of the Kurunegala area by using principles of CA modeling. Remote sensing tools, particularly satellite images, provide significant potential for urban studies by capturing changes in land cover over time (Yeh & Xia, 2021; Bhatta et al., 2010). Using remote sensing data, researchers may generate LULC maps, examine urbanization trends, and evaluate urban growth. Incorporating remote sensing data with CA models improves the precision and dependability of simulations of urban development (Mostafa et al., 2021). In this study, the combination of remote sensing analysis and CA modeling will facilitate a thorough comprehension of the temporal and spatial dynamics of urban development in the Kurunegala district.

- **Research objective:** The main objective of this study is to figure out how well the suggested zone factors by the UDA would align with the simulated urban sprawl distribution patterns. This evaluation will be done by comparing the proposed zone factors in a map to the results of simulations of urban growth modeling done with CA.
- The UDA-specified zone factors will be evaluated and assessed as a component of the study. These factors play a crucial role in determining the structure of cities and ensuring compliance with regulations. Additionally, it is crucial to acknowledge that the selected study area for comparing the zone factors was rather small in size. This choice was made due to the initial incompatibility of the UDA’s forecasts and rules with larger geographical areas.
- The approach of the study entails a thorough comparison between the anticipated results obtained from CA modeling and the zone factors developed by the UDA. This comparison serves to demonstrate the effectiveness of these zone factors in conjunction with urban growth expansions.
- The results of this research might have important consequences for policies and strategies related to urban development. It may assess if the current zone factors sufficiently consider the patterns of urban expansion in the selected study area, or whether adjustments are required.
- This study contributes to the subject of urban planning by offering empirical evidence and insights about the alignment between zoning laws and the growth patterns of cities. It provides an opportunity to propose evidence-based policy recommendations that can enhance the effectiveness of urban development in the studied area.

This study aims to enhance decision-making and promote sustainable urban development practices by focusing on its key objectives. Urban planners and policymakers will have the chance to evaluate the locations in which urban expansion is expected to occur in the future and compare the suggested zoning variables with how suitable the location is for development. Prior to the construction of
future urban development plans, it is possible to identify the specific locations that should be focused on for development or relieved from additional congestion.

1.1. Study area

The chosen study area for the CA urban growth simulation is mostly focused on the central area of Kurunegala city. Kurunegala is currently experiencing significant urbanization and is emerging as a prominent city hub. Furthermore, other significant growth hubs have emerged in different locations around the city’s perimeter, thereby influencing this process of urbanization. Thus, it has been proposed to generate future urban growth patterns within the city limits, focusing on a specific area slightly smaller than the entire district. The primary rationale for this decision was the technological feasibility, as it proved to be exceedingly challenging to manage a wider region for simulation purposes. Accordingly, this research article is comprised of the content as follows. The subsequent section 02 will discuss the literature review. Section 03 will describe the methodology of the process followed. Section 04 will discuss the results and discussions and finally, section 05 will discuss the conclusion of the research.

2. Literature Review

Urban growth is the process of how cities grow and change over time. It looks at the changes in the physical, economic, social, and natural aspects of cities and towns as they grow in size, population, and complexity (Garouani et al., 2017). Growth in cities is influenced by a multitude of interconnected elements, including economic growth, population increase, technological progress, land availability, transportation infrastructure, social and cultural transformations, government policies, and the surrounding landscape. The interaction of these elements in intricate patterns gives rise to the recurrent trends of land use, housing developments, commercial establishments, and infrastructure that are observable in urban regions. Examining urban sprawl is crucial for effective urban planning as it enables policymakers to anticipate and address issues about infrastructure development, resource allocation, settlement patterns, environmental conservation, and overall enhancement of urban living standards (Yeh & Xia, 2021).

Spatial analysis is a key part of figuring out the complicated trends and processes that drive urban growth. It looks at the connections, trends, and exchanges between places in urban settings. By combining Geographic Information Systems (GIS) and remote sensing methods, researchers can collect and analyze spatial data that is essential for modeling urban growth. These data sources include land use, population spread, building systems, and environmental factors (Mustafa et al., 2018). Together, they give a comprehensive understanding of how cities change over time (Mostafa et al., 2021). Through the use of spatial-based analysis, researchers can identify regions of expansion, ascertain the impact of various factors on urban development, and even forecast future patterns of urban growth. Furthermore, the accuracy of research on urban expansion may be enhanced by using spatial analysis and sophisticated modeling techniques such as CA models (Berberoğlu et al., 2016). This approach enables the incorporation of spatial interconnections and constraints, hence facilitating a more precise depiction of the intricate functioning of urban systems. The integration of spatial analysis and modeling provides policymakers and urban planners with a robust framework for making well-validated decisions that support sustainable urban development and
effective land use management (Vliet et al., 2009).

CA models have gained popularity in the field of urban modeling due to their ability to accurately depict the dynamic evolution of complex systems (Kuo & Tsou, 2017). These models use a grid-based system where cells change between different states based on rules that have already been set up (Syphard, et al., 2005). This replicates how land use trends change over time. CA models have several advantages, including their inherent simplicity and their ability to visually depict the interconnectedness of various components within an urban region.

CA urban growth simulation uses a grid of cells to represent the cityscape (Ullrich & Lückerath, 2020). Built-up, non-built-up, and empty are just a few of the various potential conditions that a single cell might represent. In the simulation, time is broken down into discrete increments, and each cell's state is modified based on a set of rules that determine how it moves through states depending on characteristics such as its closeness to infrastructure, its compatibility with surrounding cells, and so on (Kumar et al., 2016). Insights into the processes of urban expansion and the possible effects of various development scenarios may be gained via the use of CA models, which record spatial patterns and interconnections. Urban sprawl simulations also include agent-based modeling (ABM) (Kumar et al., 2016). ABM portrays distinct groups with unique traits, behaviors, and decision-making criteria. Spontaneous variations in urban development result from the interactions between these actors and their surroundings. To study how different agent behaviors, regulations, or incentives affect sprawl structures, researchers might use ABM, which reflects the variability and individual-level processes of decision-making that contribute to urban growth. CA modeling using CA and Markov Chains (CA-Markov) combines their best features (Ullrich & Lückerath, 2020). The urban environment is segmented into cells, much as in CA, and Markov Chains are used to predict the probability of transitions between states (YIN et al., 2008).

According to past data or expert knowledge, these probabilities of transition indicate how likely it is that a cell will shift from a single condition to a different one in a subsequent time step (Falah et al., 2020). By combining the geographic interaction represented by CA with the temporal dynamics described by Markov Chains, CA-Markov models supply an evolving description of urban expansion (Rienow, 2016). These methods are very helpful for understanding the intricate dynamics at play in the urban sprawl phenomenon.

CA models provide a versatile approach to examine several scenarios and assess the impact of policies and actions on them. However, CA models do have some limitations. Running them on a computer may be challenging, especially when simulating large urban areas over extended timeframes. Additionally, the precision of cellular automaton models is heavily reliant on the meticulous configuration of rules and parameters (Navid & Aghababa, 2013). This makes them subject to hypotheses that might not always truly reflect how things work in the real world (Mosammam et al., 2017). Calibrating and testing CA models may be challenging because of the need for historical data for calibration and future data for validation. Ultimately, CA models are a valuable tool for understanding the mechanisms behind urban expansion. However, for a comprehensive and reliable understanding of urban development, it is crucial to supplement CA models with other methodologies and domain-specific information.

It is crucial to monitor and analyze the impacts of urban expansion and LULC change to identify areas that need intervention and guide sustainable development. This is particularly important in developing nations like Sri Lanka, where planners may provide new incentives to mitigate urban sprawl (Ullrich & Lückerath, 2020). The substantial rise of the country's urban population in recent decades may be attributed to government incentives, restrictions, regional development...
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disparities, and rural-urban migration. This phenomenon has led to substantial expansion of urban areas, creating difficulties for agricultural regions located on the outskirts. The research of spatial expansion patterns is crucial in aiding city planners and politicians in guiding future development and managing the environment. Consequently, this research investigates the extent to which these patterns align with the recommended zone parameters for the given location. Through the use of this technique, the study aims to provide valuable insights to facilitate well-informed decision-making and optimize urban planning processes.

3. Methodology

The study deals with different thematic layers which were prepared using satellite imageries downloaded from USGS Earth Explorer and numerous data obtained from OpenStreetMap (OSM). LULC maps were developed from 1997 to 2022 to determine the urban growth dynamics. CA is heavily used in many different fields because they are flexible and can describe complicated dynamic systems. These mathematical models grow over discrete time steps according to a set of rules. The main reasons why CA is used so often are its ability to record emergent phenomena, its ease of application and computation, and its ability to create complicated patterns from relatively simple rules. In the field of urban growth models, CA is very useful for simulating and understanding how cities grow and change based on past data. CA has been helpful to urban planners, politicians, and scientists because they can correctly show how things change in space. CA has become a useful tool for modeling urban growth because they are easy to use, flexible, scalable, and clear. These programs can be used to model everything from simple changes in how land is used to more complicated changes like the growth of transport and infrastructure. In the field of urban planning, CA models can be used to predict how cities will grow in the future, find possible land use issues, figure out how planning policies affect cities, and identify how vulnerable cities are to natural conditions. Recent studies have focused on how CA can help with sustainable urban planning and development by showing how it can be used in many different ways to model urban growth.

3.1. Data Preparation

Multi-temporal Landsat images were downloaded from the USGS Earth Explorer website for the years 1997, 2002, 2007, 2012, 2017, and 2022. For image preprocessing, unsupervised classification was conducted with pre-defined four land use categories since it could be done without training samples.

The above model (Figure 03) shows the post-classification process followed in the Arc Map Model builder. In the post-classification process, boundary clean, majority filter, region group, set null tool and finally, nibble tool were used for highly accurate post-land use classification outputs.
3.2. Research design

By adjusting the kernel size of the pixels, it has been predominantly attempted to concern the current state of the pixels. Accordingly, the immediate neighboring pixels as well as the set of transition rules were used for the simulation phenomenon. The rules of CA were fundamentally focused on the simulation of real-world scenarios and certain exceptions were mostly concentrated whenever the threshold values of each parameter were linked with the current states of the test pixels.

The transition rules were focused on the set of conditional statements with different threshold values. The threshold values of each parameter were linked with the current states of the test pixels.

Equation 1: Test pixel sizes of the kernel

\[
A_{ij} = \begin{bmatrix} a_{i,j-1}^0 & a_{i,j}^0 & a_{i,j+1}^0 \\ a_{i,j-1}^1 & a_{i,j}^1 & a_{i,j+1}^1 \\ a_{i,j-1}^2 & a_{i,j}^2 & a_{i,j+1}^2 \end{bmatrix} \quad \text{X Neighborhood}
\]

Here, for the neighborhood, 3x3 kernel size was utilized and it was given with the best accuracy in model training. The model primarily depends on the set of transition rules and current states of the test pixels.

3.3. Process and algorithms followed in the CA model
transition rules as well as the kernel sizes which were set at the beginning. For each parameter, it is needed to set the proper threshold values and it is also needed to set the corresponding number of built-up pixels.

3.4. The parameters used for the model
These are the variables that have been used for the simulation process that were emphasized in the CA modeling framework.

3.5. Urban growth modeling

Urban growth modeling was used to forecast the future urban dissipation patterns from 2022 to 2027 while utilizing the historical LULC images.

3.5.1. Population density
The population density map was prepared using the data from the statistics department and after analyzing the population density for the year 2020, it could be identified that the town center is highly concentrated with a higher density, and moving away from the town center has a lower density.

3.5.2. Restricted areas
The restricted areas have been obtained from the data received from the land use and policy planning department and the highly restricted areas will not be used for the urban growth simulations.

3.5.3. Distance from main town centers
This factor was used for tracking the non-uniform growth that took place within the main town centers and the directional patterns of the urban growth that can be identified. Data obtained from OSM.

3.5.4. Slope
According to the slope map, there are numerous large rocks surrounding the city center of Kurunegala that are very noticeable. Additionally, most of the terrain may be characterized as being very similar. The slope map was generated with the Digital Elevation Model (DEM) acquired from USGS Earth Explorer.

3.5.5. Distance from sub-city centers
The distance from sub-city centers impacts the easy access to various urban areas. Suburban centers frequently contain important employment sites, commercial nodes, as well as vital resources. Greater proximity to these centers facilitates residents’ ability to access job possibilities, products, and services, schooling, medical care, as well as additional conveniences. Data obtained from OSM.

3.5.6. Distance from railway stations
Railway stations function as key transportation centers, providing easy access to various sections of the city as well as beyond. The proximity to train stations influences the accessibility and commutability of an area. Overall, areas close to train stations are more readily available and attract individuals with a greater degree of movement. Introducing a parameter like this into urban growth modeling assists in capturing the impact of transportation accessibility on urban expansion processes.

3.5.7. Distance from expressways
Motorways are important transportation routes that link different areas and cities across long distances at high speeds. The closeness of a region to highways impacts its ease of access and ability to connect with other areas. In close proximity to highways, the transportation of people, goods, and services is aided by more efficient and expedited transit. When included in urban growth models, this element helps measure the influence of connectivity and availability on urban development trends.

3.6. Model calibration
The model calibration was done using the satellite-based LULC maps from 1997 in this study using the CA model itself in the beginning. The model was calibrated with the best threshold values and spatially obtained the simulation results. The threshold values were tested several times to obtain a higher accuracy rate and then changing the LULC from the second land use map, the simulation was done for the next period.

E.g. Firstly utilizing the 1997 LULC map the simulation was done for the year 2002. By training the pattern to the model, it uses the 2002 LULC map to predict the LULC in 2007. Likewise, the future predictions were done up to 2027. The difference between the
two LULC maps, the spatial difference is calculated internally by subtracting the built-up pixels. The common built-up area is neglected in the subtraction process.

4. Results and discussions

Satellite land use maps were prepared and later utilized for calibrating the model. Model calibration was paid considerable attention to obtaining a higher accuracy for training the model and subsequently, for simulation of the urban growth development within the area.
Here, the true urban concentrations as well as the simulated urban concentrations that are derived from the process have been listed accordingly. The CA model was built to simulate future urban growth while using historical urban concentrations. In the above approach, a 2002 true urban concentration map was prepared and then used for the simulation. Accordingly, a 2007 urban concentration map was generated. This map was compared with the true urban area extracted map as shown above in Figures 11 and 14. Utilizing the same process, the simulation was carried out while comparing the generated results.

4.1. Simulated LULC maps for the selected years

Along with the urban area concentrations for the region, land use maps were also prepared with the past data using the model. As the land use types, urban, agricultural areas, water, and vegetation were selected. These were used to compare with the true land use maps which were prepared using an unsupervised classification process under Arc Map 10.8 and validated the simulation results for the proceeding steps.
After generating the results, the accuracy assessment was conducted and it was done using the model itself. Using the calibrated model, the accuracy assessment for the model was calculated and the generated results for each step are mentioned below.

### 4.2. Accuracy assessment

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Accuracy assessment percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>97.340839 %</td>
</tr>
<tr>
<td>2012</td>
<td>98.044863%</td>
</tr>
<tr>
<td>2017</td>
<td>95.476666 %</td>
</tr>
<tr>
<td>2022</td>
<td>91.022048 %</td>
</tr>
</tbody>
</table>

As per the derived results (Table 01), there is a higher accuracy in the generated results in each stage. Consequently, using 2022 as the urban concentration Map, it was attempted to derive the urban expansion map for the next five-year time period, which is for 2027 (Simulation).

### 4.3. Simulation

The urban area concentration in 2022 was 199.311039 sq. km and it was simulated to 2027 to analyze the urban growth distribution within the area and it was able to identify that the urban growth distribution is 309.533658 sq. km. Therefore, there will be a 110.222619 sq. km increment in the urban growth distribution when it is reaching 2027. Thereby, the increment in percentage can be estimated as 55.31% as a whole. Along with the urban growth increment, there will be numerous other impacts on the environment as well as other segments. Consequently, a development suitability map was analyzed with the proposed zone factors by the UDA for the development of the 2030 period.

### 4.4. Development suitability analysis

The purpose of a development suitability analysis is to identify areas that are suitable for residential, commercial, industrial, and recreational development. By comprehending the appropriateness of land for particular uses, urban planners can make well-validated decisions regarding the location choice of various forms of development. This aids in preventing...
unplanned growth and encourages a well-planned urban environment. For the identification of the development suitability, an Arc Map model was used with different parameters. The land use layer which was prepared using the USGS data as well as from OSM, weighted overlay was carried out for the proper identification of the developable areas of the region.

A development appropriateness assessment may be used to identify the most appropriate areas for residential, commercial, or industrial development. The provided information is crucial for urban planners, who may use it to drive growth in a sustainable and fair manner. Determine what factors are most significant for the proposed development can be obtained from a suitability analysis with different factors taken for the weighted study.

Criterion-weighted overlay map will display the range of values for each criterion throughout the research region. It must be first given weights to each criterion before making a weighted overlay map. Each criterion's weight represents its significance in light of the development type. After the criterion maps are weighted, they are superimposed on top of one another and weighed using the given weights. The generated weighted overlay map demonstrates how viable each location is for further development. The following map shows the development suitability which has been prepared using Arc Map 10.8.

Figure 25. Development suitability from Arc Map
Out of the whole region described earlier, a specific area was chosen since UDA has put up the zone factors only for the Municipal council area inside Kurunegala. Thus, that area was clipped from the above region. The following maps comprise a separate analysis for the clipped area, which is constituted of urban area distribution, development suitability, proposed zone factors, and proposed development activities.

Figure 26. Urban area concentration - 2027

Figure 27. Development Suitability

Figure 28. Proposed Zone factors

Figure 29. Proposed development activities
As Figure 28 shows, these zone factors for the region were obtained from the UDA Kurunegala, which was targeted to develop the development plan for 2030. The approach to developing the zone factors for each specific area depended on the development ability of the area as well as the future targeted commercialization policies.

As per the urban growth simulation using CA, the development suitability, which was derived from the Arc GIS analysis using the data from OSM, would mostly align with the development trend but when it comes to the zone factor analysis, the proposed zone factors are not quite aligned with the proposed urban growth dissipation of the area. Most of the environmentally sensitive areas are also included in the higher development zones with a higher value for the zone factors and consequently, it could be emphasized that the proposed zone factors would not be highly accurate as a whole for the development further into the future.

5. Conclusion

This study mainly focuses on the spatiotemporal urban growth simulation using the CA model from 1997 to 2027 within the Kurunegala town center. After analyzing the LULC distribution through the remote sensing techniques, it was able to discern a rapid change in the urban growth distribution, and the urban concentration increased by 55.31% when reaching 2027 from 2007. The model’s accuracy in the simulation process was tested from the CA model itself after the calibration process by overlaying the existing and predicted urban growth values. Consequently, it was able to generate a higher accuracy in the prediction process which was obtained higher than 90%.

In conclusion, CA modeling served as the basis for this research and the effects of urbanization on the Kurunegala District. The development flexibility of the area was evaluated by taking into account numerous spatial features and restrictions, yielding useful information for urban planning and sustainable growth. To successfully manage urban expansion, the findings of the modeling show that a well-planned strategy for development suitability is required. The research highlighted possible areas of future urban concentration. Urban planners and decision-makers may use this data to efficiently allocate land and construct the required infrastructure to handle a growing number of communities. This study's use of CA modeling provides a useful tool for city planners and policymakers interested in simulating and forecasting urban development trends. It allows for a thorough comprehension of the complicated dynamics involved in urban growth by factoring in a wide range of geographical elements and restrictions.

By looking at the main goals, this study hopes to help and improve how decisions are made and how cities are built in a sustainable way. Urban planners and policymakers might analyze the prospective growth regions of cities and evaluate the compatibility of recommended zoning factors with the area's development potential. Prior to formulating future strategies for urban development, it is essential to ascertain the areas that need more expansion or a reduction in population size. This research technique aims to comprehensively understand the impact of urban area increase on future urban development densification. This representation would be produced by several organizations and would adhere to the recommended zone factors and the appropriateness of the location for development. Furthermore, this work addresses some knowledge gaps in the field of urban growth modeling and development appropriateness evaluation, particularly in relation to the Kurunegala District. As the main objectives stated, to simulate the urban growth for the future and compare the generated results with the development suitability and the proposed zone factors were covered in this research process accordingly. This study's results and interpretations may be used as a platform for more investigation and as
supporting evidence for urban planning decisions. In conclusion, the CA and development suitability analysis-based urban growth modeling framework offers a supportive method for controlling and directing urban expansion in the Kurunegala District. This study provides a holistic understanding of the difficulties and prospects of sustainable urban development in the region by examining a wide range of factors, including land use planning, infrastructure growth, and development, conservation of the environment, and social and economic factors. The results of this research may be used by politicians, urban planners, and other interested parties to develop a more deliberate, sustainable, and hospitable urban environment.

6. Limitations
The use of readily accessible resources, such as zoning regulations from the UDA, land-use data, and geographical data, would facilitate the modeling and analysis procedure. It is crucial to acknowledge that the practical use of this study is restricted to the specific location chosen for comparison. Insufficient research could prevent the straightforward application of the findings to broader regions.

Acknowledgment
ERASMUS + funded the LBS2ITS project for equipment granted to Urban Simulation Lab, Department of Town and Country Planning, University of Moratuwa.

7. References


