# Project-Based Urban Dynamics: A Novel Method for Assessing Urban Sprawl


**Nir Fulman**

Department of Geography and Human Environment, Porter School of Environmental Studies, Tel Aviv University, Israel
GIScience Research Group, Heidelberg University, Germany

**Yulia Grinblat**

Heidelberg Institute for Geoinformation Technology (HeiGIT) gGmbH at Heidelberg University, Germany

**Itzhak Benenson**

Department of Geography and Human Environment, Porter School of Environmental Studies, Tel Aviv University, Israel



## Abstract

We present a new approach to categorizing different types of urban development, namely infilling, fringe, and leapfrogging, based on construction projects as the fundamental unit of analysis. We focus on the role of the leapfrogging projects as seeds for new developments, leading to urban sprawl extending beyond statutory plans. To examine this phenomenon, we analyze the 50-year growth of three major Israeli cities: Netanya, Haifa, and Safed and the 5-year dynamics of 66 cities in Israel that account for 68% of the country's population. Our investigation utilizes extensive databases of Israeli development plans, along with high-resolution aerial photographs covering the investigated areas and time periods. These datasets were supplemented by detailed Israeli databases encompassing roads, buildings, and other infrastructure elements, compiled by the Israeli Mapping Centre for the year 2018. Our analysis reveals that although most construction projects in Israel adhere to land-use plans, urban sprawl in Israel remains highly unpredictable. Leapfrogging is specific in terms of both place and time, attracts additional development nearby, and forces the divergence from development plans. We conclude that urban modelers' view of urban dynamics being driven by common and systematic forces, is unrealistic. Instead, every city has its specific and self-enforcing development drivers that define its land-use dynamics. This explains the limited success of the Cellular Automata (CA) models in explaining and predicting urban dynamics.



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## 1 Introduction

Urban development is complex and only partially predictable, as illustrated by the limited ability of Cellular Automata (CA) to predict Land-Use/Land-Cover (LULC) dynamics ([3]). This is particularly true for leapfrog development beyond the current city boundary ([2]). Leapfrogging attracts additional development, and this positive feedback mechanism may override statutory plans ([1]) and significantly modify the city's spatial dynamics ([4]), increasing their unpredictability. To mitigate deviations from the development plans, it is crucially important to estimate the role of leapfrogging in urban dynamics. Our paper proposes a new method for identifying leapfrogging and assessing its effects by studying a large database of Israeli development plans versus real development.



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We depart from the conventional raster-based analysis of satellite images by analyzing urban sprawl based on the fundamental unit of urban development – the development project. Our view of urban dynamics centers on three types of urban development - infilling, fringe, and leapfrogging. We quantify the extent and attractiveness of leapfrog projects for further construction nearby that contributes to non-planned sprawl. Our study exploits unique county-wide Israeli data on land-use dynamics: aerial photographs, development plans starting from the 1960s, and comprehensive databases of building footprints, land use, and road data, all provided by the Israeli Mapping Center (IMC). The research focuses on a 53-year sprawl of three Israeli cities – Netanya, Haifa, and Safed – from 1964 to 2018, and the sprawl in 66 Israeli cities with a population exceeding 15,000, between 2013 and 2018.

## 2 The data

To assess the effects of leapfrogging, we investigate two datasets. The first represents long-term dynamics in three cities that differ in their properties: Haifa, a metropolitan city with a population of 283,000 in 2018; Netanya, a mid-sized city near Tel Aviv (217,000); and Safed, a small city located far from metropolitan areas (36,000). In each city, we study the LULC dynamics of 6-km width transects that start in the city's CBD and extend beyond city boundaries to open spaces. The second dataset represents LULC dynamics in 66 cities housing 68% of Israel's population, between 2013 and 2018.

Aerial photos covering the transects at a spatial resolution of 25 cm, were obtained from the IMC for the years 1964, 1972, 1983, 1993, 2000, and 2008. Based on each photo, polygons of building constructions and roads were manually digitized. Buildings and road layers for 2013 and 2018 were obtained from the IMC database for these years. To estimate the year of building construction we compared the IMC layer of buildings in 2018 to the corresponding aerial photography building layer, and assigned the year in which a building first appeared in the aerial photo as its construction year. The information on the building's use was also acquired from the IMC layer for 2018 and aggregated into residential, industrial, public, and others. Additionally, we used the IMC 2018 road layer to estimate the year of road construction. All these data were matched to layers of construction plans. Similarly, we matched the IMC layers and development plans for the years 2013 and 2018 for the 66 cities.

Our assessment of the leapfrogging is based on the recognition of the urban fringe – the border area between the built-up and non-built-up parts of the city, and development projects – the basic units of urban development that consist of one or several buildings.

## 3 Identifying the urban fringe and development project

### 3.1 Recognizing the urban fringe

We recognize the urban fringe by examining, annually, the continuity of built-up ($BU$) and non-built ($NB$) areas. Based on the average distance between buildings in the city, we perform this examination at a resolution of 50m and consider a 50x50m (vector) cell as $BU$ if at least 5% of its area is covered with buildings. The cell is a part of the continuous $BU$ patch if at least 7 of its 8 neighbors in the 3x3 neighborhood are also $BU$. The same rule applies to $NB$ cells, for identifying continuous $NB$ patches. An urban fringe is the rest of the area. To group adjacent cells of the $BU$ or $NB$ types into continuous regions we apply a connected-component labeling algorithm with orthogonal and diagonal (8-cell) connectivity.

The fringe areas $F(t_n)$, estimated at the year $t_n$, can be of 3 types (Figure 1):

- $F(t_n)$ is an inner fringe, denoted as $F_i(t_n)$, if all cells adjacent to it are of the $BU$-type.

- $F(t_n)$ is a leapfrogging development, denoted as $F_l(t_n)$, if all cells adjacent to it are of the $NB$-type.
- $F(t_n)$ is an outer fringe, denoted as $F_o(t_n)$, otherwise.

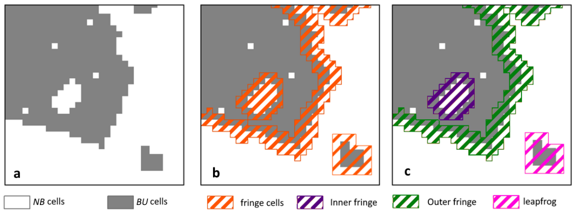


**Figure 1** Recognition of a fringe area: (a) construction of $BU$ (grey) and $NB$ (white) continuous areas; (b) fringe area; (c) inner fringe, outer fringe, and leapfrog.

### 3.2 Recognition of development projects

Definition of a development project: Buildings $b_1, b_2, ...b_k$ belong to the same construction project $P(t_n)$ that starts in the year $t_n$, if (1) they are all recognized, for the first time, in the aerial photo of the year $t_n$, (2) there is no road between any pair of them, (3) there is no $NB$ areas between them, and (4) they share the same land-use - residential, industrial public, other, determined based on the attributes of the IMC building layer. The spatial extent of the project $P(t_n)$ is established as follows:

1. Construct Voronoi coverage $V(t_n)$ based on the centroids of all buildings existing at $t_n$. Assign land use type of the building to its Voronoi polygon (Figure 2a).
2. Construct layer $R(t_n)$ of roads at the year $t_n$, representing roads as polygons (Figure 2b).
3. Erase road polygons $R(t_n$ from $V(t_n)$, to obtain corrected Voronoi coverage $V_c(t_n)$ (Figure 2c).
4. Overlay $V_c(t_n)$ and grid G that defines the resolution of our view of the city, currently 50x50 m (Figure 2d).
5. Erase NB polygons (constructed for the fringe assessment) from $V_c(t_n)$ (Figure 2e).
6. Obtain $P(t_n)$ by merging adjacent Voronoi polygons of the same land-use (Figure 2f).

To recognize the changes in the urban patterns between the moments $t_{n-1}$ and $t_n$ we overlap projects that first appeared in the year $t_n$ with the fringe $F(t_{n-1})$. If a certain project $P(t_n)$ overlaps $F_o(t_{n-1})$, then this project is a fringe-expansion. If $P(t_n)$ overlaps $F_i(t_{n-1})$ or is located within the city borders, it is an infilling project. If $P(t_n)$ overlaps $F_l(t_{n-1})$, then it is an old-leapfrog, and if $P(t_n)$ does not overlap $F(t_{n-1})$, it is a new leapfrog (Figure 3).

## 4 General view of leapfrogging

The amount of new development in Netanya, Haifa, and Safed changed over the 50-year observation period (Figure 4). The construction activities in Haifa and Safed peaked in the early 1990s, while Netanya's period of rapid development was in the early 2000s. The decline in development rate from the year 2000 onwards in all three cities reflects the national trend.

Infilling is the least prevalent form of development in the three cities, accounting, besides the year 2013 In Haifa, for less than 5% of the total construction during the entire period. In the large Haifa and Netanya, fringe projects make up 80-90% of the developed area, while leapfrogging accounts for the remaining 10-20%, except for two spikes in Haifa in 2008 and 2013 with 20-30% of leapfrogging, and Netanya in 2013 with 40% of leapfrogging (Figure 5). In the smaller Safed, the share of leapfrog fluctuates between 25% and 80%, averaging 45%.


**Figure 2** Project construction: (a) Voronoi coverage $V(t_n)$ of buildings; (b) Road polygons $R(t_n)$ (c) Road polygons $R(t_n)$ erased from the $V(t_n)$; (d) grid $G$ classified into $BU$ and $NB$ cells; (e) $NB$ polygons erased from the $V_c(t_n)$; (f) $P(t_n)$ is obtained by merging adjacent Voronoi parts of the same land-use.

In the country-wide case of the sprawl of 66 cities between 2013-2018, the average share of leapfrog development is 13% of the total developed area, while the variation of this share is substantial, and the standard deviation of it is 15%. The relationship between population size and the share of leapfrog development is not statistically significant, while if we split the cities into 3 groups – above 100K, 50-100K, and below 50K population, the average shares, by groups, increase from 9% to 14%, and 16%, respectively (Figure 6).

## 4.1 Adherence to development plans

We study adherence to statutory plans by overlaying the layer of the development projects started during the period $[t_n, t_{n+1}]$ and the layer of the development plans for the same period. In this way, we can identify constructions that sprawl beyond the planned areas (usually, to the open lands, agriculture, or forest). Overall, Israeli developers consistently adhere to zoning plans. In Netanya, the overlap is almost 100%, while in Haifa and Safed, 8% to 10% of leapfrog projects violate plan constraints. In the county-wide case, developers also closely adhered to the statutory plans. On average, 94.6% of the projects' area is within the planned border, with 14% of leapfrog projects violating development plans.

## 4.2 Residential leapfrog project as a seed for future development

We consider leapfrog project $P(t_n)$ erected during period $[t_{n-1}, t_n]$ as an active urban seed if other projects are erected 50 m or less from $P(t_n)$ during the next period $[t_n, t_{n+1}]$. Otherwise, the leapfrog project is passive. Active leapfrogging expresses the system's positive feedback, and its strength can be assessed based on long-term data only. Over 50 years, the share of leapfrog projects in Safed, Netanya, and Haifa that remain passive is 61-68%. Yet, 47-63% of

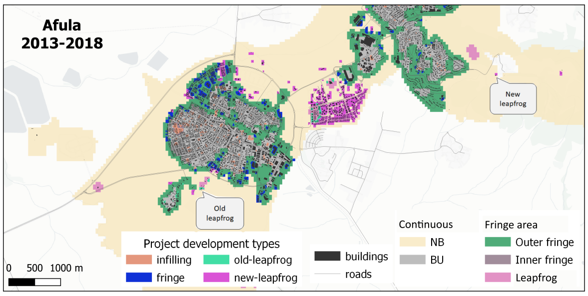


**Figure 3** Leapfrog, infilling, and fringe projects in Afula city between $t = 2013$ and $t = 2018$.

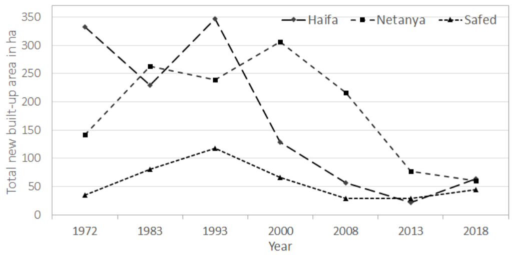


**Figure 4** The new built-up area (ha), along the transect, in Haifa, Netanya, and Safed.

new residential leapfrog projects become active seeds and stimulate additional development. For leapfrog projects of industrial and public land uses, the share of active seeds is much lower and varies between 25-32% and 32-45%, respectively. Residential and industrial seed projects attract projects of the same kind in over 90% of cases across all three cities. Active public projects, on the other hand, exhibit city-dependent attractiveness patterns.

## 4.3 Urban fringe expansion towards the leapfrog projects

Attracting new constructions, the leapfrog projects become the seeds of unpredictable dynamics of the urban built-up pattern. However, in time, some of these self-organizing areas are absorbed by the regular sprawl of the continuous part of the city. One needs long-term data to estimate the rate of this absorption and to this end, we estimate the percentage of leapfrog projects $P(t_n)$ for which the distance to the nearest project that belongs to the urban fringe becomes zero in time. This assessment demands three sequential observations and we employ it for projects erected until 2008. Estimating this rate, we see that most of the leapfrog projects become absorbed by the city. In Safed, 25% of the projects remain unabsorbed; in Haifa, the share is 31%; and in Netanya, it is 26%.

# 5 Conclusions

About 13% of the development projects in Israel are leapfrogging and only 14% of these projects, that is, less than 2% of all constructions, violate statutory plans. In time, most of these projects become absorbed by the city, however, before this happens, half of residential and a third of other leapfrog projects serve as seeds for further sprawl. For this reason, leapfrogging often necessitates updates to existing development plans and infractions can be critical for the development trajectory of the city. The importance of leapfrogging as a possible dynamic phenomenon that averts the planned city development trajectory can only be estimated with long-term and high-resolution data on urban dynamics, as above.

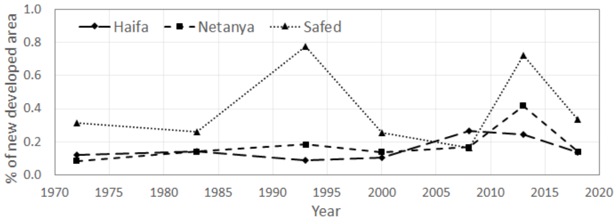


**Figure 5** The dynamics of the share of leapfrogging development in Haifa, Netanya, and Safed.

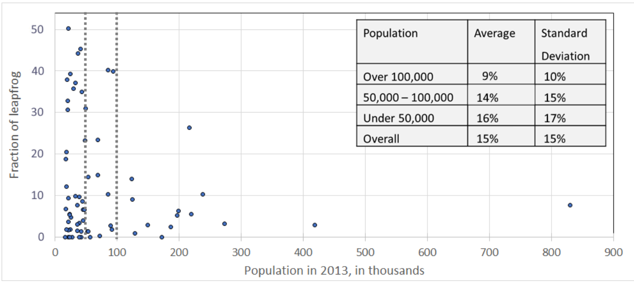


**Figure 6** The share of the leapfrogging development by cities, depending on their population.

Safed, enveloped by open areas and forests, Haifa with partial constraints, and Netanya, fully surrounded by agricultural lands and other settlements - each city exhibits a unique development pattern, and this pattern is not related to the size of the city. The growth of these cities is mainly defined by historical events, like development peaks in the 90s and early 2000s following mass immigration from the former USSR. We hypothesize that it is this interaction between the external factors and positive plan-violating feedback that makes urban sprawl unpredictable. We plan to explore this unpredictability with an agent-based model of urban growth, whose mechanisms and parameters will be based on the above results.

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