Method Article

Urban growth prediction with parcel based 3D urban growth model (PURGOM)

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A B S T R A C T

While cities grow horizontally over natural areas, they also grow vertically with high-rise construction in time. The Floor Area Ratio (FAR) is defined as the ratio of the amount of construction area on a parcel to the parcel area. FAR is one of the essential indicators for detecting and measuring 3D (three-dimensional) change. The amount and trends of change differ for each urban settlement and on its internal dynamics.

This study consists of two stages: determining and modeling the variables and their weights that affect the FAR values and generating future estimates. First, the criteria affecting the growth trends between the years of 2012 and 2019 in the study area of Saray were examined as five groups at the parcel level with statistical and spatial analysis. It has been determined that the criteria; accessibility, accessibility in line with planning decisions, zoning and land-use decisions, land values, and the built environment affect the FAR value distribution. As a result of the analysis, the selected criteria were evaluated with Geographical Information Systems (GIS) and the weighted linear combination method. The probable spatial distribution of FAR coefficients of each parcel was found. The FAR coefficients obtained were calibrated by real FAR values for 2019. Future predictions for the years 2030 and 2040 were revealed according to the demand scenario. As a result, it was determined that there is a construction pressure on the urban center and near the transportation routes.

The primary purpose of this study is to determine current trends by creating a 3D urban growth model based on parcel-level FAR values, making predictions, and producing decision support tools for city managers.

- Determination of criteria and weights according to spatial dynamics of the study area.
- Determination of the amount and type of urban growth demand specific to the study area and its compatibility with different scenarios.
- Prediction of parcel-based 3D urban growth

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https://doi.org/10.1016/j.mex.2021.101302
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**Keywords:** Vertical urban growth model, Parcel-based cellular automata, Urban development, Scenario simulation, 3D growth model, Urban form, Weighted linear combination, Cellular automata

**Article history:** Received 30 January 2021; Accepted 5 March 2021; Available online 11 March 2021

**Specifications table**

| Subject Area: | Environmental Science |
|---------------|-----------------------|
| More specific subject area: | Urban growth modeling |
| Method name: | Parcel Based 3D Urban Growth Model (PURGOM) |
| Name and reference of original method: | A novel method is developed in this paper, however inspired from early literature: Koziatek, Olympia, & Dragičević, S. (2019). A local and regional spatial index for measuring three-dimensional urban compactness growth. Environment and Planning B: Urban Analytics and City Science, 46(1), 143-164. https://doi.org/10.1177/2399808317703983 Koziatek, O., Dragičević, S., & Li, S. (2016). Geospatial modelling approach for 3D urban densification developments. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 41(July), 349–352. https://doi.org/10.5194/isprsarchives-XLI-B2-349-2016 Koziatek, Olympia, & Dragičević, S. (2017). iCity 3D: A geosimulation method and tool for three-dimensional modeling of vertical urban development. Landscape and Urban Planning, 167(June), 356-367. https://doi.org/10.1016/j.landurbplan.2017.06.021 |
| Resource availability: | n/a |

**Background information**

Urban areas are expanding horizontally and rising vertically due to the population growth. The amount and type of demand shape the form of urban growth. The biggest reason for the amount of demand can be considered as population growth and citywide planning studies. Several factors have a crucial role in determining the type of demand, such as the households' living habits, income levels, and vehicle ownership rates. Horizontal urban growth adversely affects natural areas on the urban periphery, while vertical urban growth may negatively affect the microclimate. In order to create more sustainable and livable cities, it is most effective to investigate the effect of existing urban dynamics on urban growth patterns and prevent problems before they occur. Therefore, studies aiming to estimate and model the quantity and quality of urban growth are frequently encountered in the literature [2].

Statistical models [18], agent-based models [4], artificial neural networks [1,28], Markov chains [14,23] and cellular automata [2,31,33,36] are the well-known modeling technics of urban growth. There are also models in which more than one method and technique are used together to take advantage of these techniques' strengths and reduce their weaknesses.

Cellular automata can be easily defined and applied to various urban areas. Urban interactions do not produce linear results. The cellular automata allow modeling of this reality, and work in coordination with GIS paved the way for the technique to become widespread in urban models. A typical cellular automata model contains five essential elements: Cells, the states the cells can take, time intervals, transition rules, and neighborhood [24].

Cellular automata models are frequently utilized by integrating with other urban models. Economic models and cellular automata, Markov chains and cellular automata [11,20], artificial neural networks and cellular automata [16,26], agent-based models, and cellular automata [21,27] system dynamic, and cellular automata [12,13] can be used together to achieve much more realistic results.

The horizontal growth of urban areas is a commonly investigated growth type. However, 3D growth modeling is relatively new. The changes that cities experience vertically are related to the building’s density and, therefore, the population density. The increase in population density causes pressure on infrastructure, especially transportation. At the same time, the insufficiency of urban facilities and
green areas has become crucial. In this context, 3D change detection [6,19,22,29,37] and 3D growth estimations [3,9,15,17,32,34,35] models are developed. 3D growth is considered as high-rise building in most models. Although vertical growth in real life is related to floor heights, it cannot be explained only by floor height. Other factors such as building coverage areas, total construction amount, and FAR values should also be taken into consideration at the same time.

FAR is one of the most effective tools available to measure urban spatial change trends over time. It is explained as the ratio of a building’s total construction area to that building’s parcel area. The increase in the amount of the FAR values causes the building’s construction area to increase and the building’s density in the urban area to increase consequently. The decrease in the FAR means a decrease in the building density. To keep building density within certain rates concerning the size of an urban area is one of the primary duties of urban managers to form livable and sustainable urban areas at a human scale. Although there is no common consensus on the ideal ratio among scholars, this ratio will likely vary in line with each urban settlements’ unique characteristics. Simultaneously, even within the same urban area, these ratios are likely to be gradual at a level that might meet the needs of various socioeconomic layers of the society.

Within the scope of the study, a parcel-based urban growth model was created in a GIS environment. It is argued that five groups of criteria, namely, proximity to the facilities in the current situation, proximity to the facilities in line with planning decisions, zoning and land-use decisions, socioeconomic structure, and built environment, are influential in the distribution of future FAR values. Criterion weights were determined by spatially and statistically analyzing the relationship between each parcel’s current FAR values and the mentioned criteria. The obtained weights were evaluated with the weighted linear combination method, and the model result values were attained. Model results have been calibrated by comparing them with FAR values for 2019. In the model, changes in population, FAR values, and total construction area between 2012 and 2019 are also analyzed. The type and amount of demand assessed by analyzing occurred change between 2012 and 2019. The urban area is divided into four zones: the center, the mid-center, the middle, and the outer periphery. Change has been designated as new development and transformation. With the help of calibrated model results and demand type and quantity, probable urban growth patterns for 2030 and 2040 are estimated.

A comprehensive evaluation of the criteria that affect the FAR values, the use of parcels as the smallest unit in which urban growth occurs, the determination of the criterion weights, the demand-type, and the amount by using the trends of the study area constitute the original aspects of the proposed model.

Study area

The urban area of the Saray District of Tekirdağ province was chosen as the model application area. The reason for choosing the study area is; the convenient size of the urban area for the high-resolution urban growth model and data availability. The population of the area in 2019 is 27,204 [30]. As a small-medium sized city [5,25], it has not witnessed significant population changes in the historical process [30]. However, due to its proximity to Istanbul, one of the largest metropolitan settlements in the world, and its proximity to the settlements of Çorlu and Çerkezköy, where decentralized industrial areas from Istanbul are located, it is likely to face urban growth pressure with the population increase in the near future [7]. Saray district center is adjacent to Kirklareli province in the northwest and Istanbul province in the southeast (Fig. 1).

Data and model structure

The building coverage area, number of floors, building usage, cadastral parcels, parcel ownership status, spatial zoning plan decisions, and land values data of 2012 were obtained from Saray Municipality. The building coverage area data for 2019 was created within the scope of the study with the help of Google satellite images by visual interpretation and raster digitization and field studies. Google satellite images was used to draw contours of buildings and field studies are done to define
building floors [10]. The raw data obtained were compiled using Esri’s ArcMap GIS program, version 10.7 [8], simplified, and made ready for use.

The study’s spatial scope consists of cadastral parcels that could be subject to residential and commercial functions. While the FAR values occur under the influence of various criteria on these parcels, different FAR value decisions are made and implemented by the administrations according to the needs of the relevant use in public facilities, industrial and military parcels. Therefore, existing and planned facility, industry, and military parcels are excluded from the model. Fig. 2, shows the relevant parcels.

The proposed model consists of mainly seven stages. Firstly criteria and sub-criteria that influence the FAR values are defined by literature review and descriptive statistics. Secondly, for each criterion, weights were obtained thanks to correlation analysis. Thirdly, coefficients for each breaking point of sub-criteria are determined. Each criterion combined and model values were attained in the next stage. After that, the type and amount of growth demand are evaluated. Lastly, a simulation was done by using model values and growth demands. Fig. 3, shows the flowchart of the methodology.

**Determination of criteria and sub-criteria**

The relationship of each criterion is questioned with built-up parcels’ FAR values. Current values are compared spatially and statistically according to proximity, planning decisions, natural structure, built environment, and socioeconomic variables. A total of 26 sub-criteria under five main criteria was examined. Criteria and sub-criteria that were not found to be in a significant relationship with the distribution of FAR values specific to the study area were removed from the model at the end of this stage. The level of relationship was screened by correlation analysis. If the value of correlation coefficient lower than 0.15, the related sub-criteria is removed from the model. Although the correlation coefficient of the sub-criteria primary road connection is lower than this value, it has kept for promising effect for future. Sub-criteria extracted from the model are proximity to existing industrial and green areas, proximity to proposed industrial and green areas in the plan, slope, aspect, elevation, proximity to river beds, and geological structure. However, the neighborhood was analyzed in 3 different circular neighborhood types, 50, 100, and 200 m. It was found that the 50 m neighborhood produced relatively significant results in modeling the distribution of the FAR values.
The selected criteria are given in Figs. 4–8. The sub-criteria weights and the coefficient values of the breaking points are shown in Tables 1–5.

The process of neighborhood and proximity analysis

For the proximity analysis, the geometric center of each parcel was considered. The perpendicular distance of the center of the parcel to the road centerline is measured in proximity to the roads. The center of the relevant facility parcel is taken as a basis for proximity to urban facilities. For the neighborhood analysis, a 50 m radius circular neighborhood from the geometric parcel center is assessed (Fig. 9). The Eq. (1) shows the calculation of the mean FAR values in the neighborhood.

\[ N_a = \frac{\sum_{i=1}^{n_a} F_{in}}{n_a} \]

- \( N_a \) = Mean FAR values of the parcel \( a \) in the 50 m circular neighborhood
- \( F_{in} \) = FAR value of the neighboring parcel \( i_n \)
- \( I_{1...n} \) = Neighboring parcels of parcel \( a \)
- \( n_a \) = Total parcel number of neighborhood

Weights of sub-criteria

The weights of the sub-criteria were determined based on the relationship between the FAR values of all the built parcels and all built-up parcels’ criterion values. Correlation analysis was used at this stage. While correlation analysis measures a relationship between two variables, it does not provide information about the cause and effect relationship. It is considered a suitable tool to determine the direction and nature of the relationship between them since the analyzed criteria are argued to be related to the FAR values. The correlation coefficient can take a value between −1 and +1. A positive correlation coefficient indicates a parallel relationship between the two variables, while a negative
value means that one variable increases when the other decreases. The higher this value, the stronger the relationship between the two variables. All correlation analyzes performed were found to be significant at a 0.05 reliability level. Eq. (2) was used while determining the sub-criterion weights.

\[
W_i = \frac{C_{oi}}{\sum_{i} C_{oi} C_{o}} \tag{2}
\]

- \( W_i \) = Weight of sub-criterion \( i \)
- \( C_{oi} \) = Correlation coefficient of sub-criterion \( i \)
- \( C_{o} \) = Total correlation coefficient of all sub-criteria
- \( I_1, \ldots, I_n \) = Sub-criteria

**Coefficients of breaking points**

Each sub-criterion was divided into breaking points according to the criterion’s characteristics, and average coefficient values were determined for each breaking point. The breaking points were
Fig. 4. Proximity analyses based on the existing situation in 2012.

Fig. 5. Proximity analysis based on zoning plan decisions.

determined with the help of the experiences and expert opinions in the analysis process. While using these values, the coefficient of each breaking point was determined for all sub-criteria. Eq. (3) was used while determining the coefficient.

\[
C_{bpi} = \frac{Fbp_i}{\sum_{bp} Fbp_n}
\]  

(3)
Fig. 6. Planned FAR values and land-use decisions.

Fig. 7. Built environment.

Fig. 8. Land prices.

Fig. 9. Process of proximity and 50 m radial neighborhood analysis.
Table 1
Proximity based on the existing situation and related statistics.

| Criteria          | Sub-criteria       | Correlation Coefficients | Weights | Breaking Points (m) | FAR Coefficients | Graphs (x-Break Points, y-FAR) |
|-------------------|--------------------|--------------------------|---------|---------------------|------------------|--------------------------------|
| Current Proximity | Secondary Roads    | −0.3035                  | 0.06    | 0–50                | 2.18             | 0.36                           |
|                   |                    |                          |         | 50–100              | 1.30             | 0.21                           |
|                   |                    |                          |         | 100–200             | 1.27             | 0.21                           |
|                   |                    |                          |         | 200–500             | 0.92             | 0.15                           |
|                   |                    |                          |         | 500+                | 0.42             | 0.07                           |
| City Center       | −0.4515            | 0.09                     | 3.02    | 0–250               | 0.41             |                                |
|                   |                    |                          |         | 250–500             | 1.58             | 0.21                           |
|                   |                    |                          |         | 500–750             | 1.26             | 0.17                           |
|                   |                    |                          |         | 750–1000            | 0.87             | 0.12                           |
|                   |                    |                          |         | 1000+               | 0.64             | 0.09                           |
| Health Facilities | −0.2475            | 0.05                     | 1.87    | 0–200               | 0.34             |                                |
|                   |                    |                          |         | 200–500             | 1.28             | 0.23                           |
|                   |                    |                          |         | 500–1000            | 1.03             | 0.19                           |
|                   |                    |                          |         | 1000+               | 1.32             | 0.24                           |
| Educational       | Facilities         | −0.347                   | 0.07    | 0–200               | 1.86             | 0.46                           |
|                   |                    |                          |         | 200–500             | 1.23             | 0.30                           |
|                   |                    |                          |         | 500–1000            | 0.64             | 0.16                           |
|                   |                    |                          |         | 1000+               | 0.33             | 0.08                           |
| Official Facilities | −0.416             | 0.08                     | 2.03    | 0–200               | 0.43             |                                |
|                   |                    |                          |         | 200–500             | 1.34             | 0.28                           |
|                   |                    |                          |         | 500–1000            | 0.94             | 0.20                           |
|                   |                    |                          |         | 1000+               | 0.43             | 0.09                           |

\[ Cbp_i = \text{Coefficient of breaking point } i \]
\[ Fbp_i = \text{Mean FAR value of breaking point } i \]
\[ Fbp_n = \text{Total FAR values of all breaking points} \]
Table 2: Proximity based on the zoning plan and related statistics.

| Criteria                    | Sub-criteria          | Correlation Coefficients | Weights | Breaking Points | FAR Coefficients | Graphs (x-Break Points, y-FAR) |
|-----------------------------|-----------------------|--------------------------|---------|-----------------|------------------|-------------------------------|
| Planned Proximity           | Planned Secondary Roads | -0.2535                  | **0.05** | 0–50 1.55       | 0.35             | ![Graph](secondary_roads.png) |
|                             |                       |                          |         | 50–100 1.02     | 0.23             |                               |
|                             |                       |                          |         | 100–200 1.03    | 0.23             |                               |
|                             |                       |                          |         | 200–500 0.73    | 0.17             |                               |
|                             |                       |                          |         | 500+ 0.07       | 0.02             |                               |
| Primary Road Connections    | -0.0585               | **0.01**                 |         | 0–200 0.29      | 0.09             | ![Graph](primary_roads.png)   |
|                             |                       |                          |         | 200–500 0.57    | 0.18             |                               |
|                             |                       |                          |         | 500–1000 1.01   | 0.33             |                               |
|                             |                       |                          |         | 1000+ 1.22      | 0.39             |                               |
| Health Facilities           | -0.2405               | **0.05**                 |         | 0–200 1.26      | 0.28             | ![Graph](health_facilities.png) |
|                             |                       |                          |         | 200–500 0.81    | 0.18             |                               |
|                             |                       |                          |         | 500–1000 1.43   | 0.32             |                               |
|                             |                       |                          |         | 1000+ 0.95      | 0.21             |                               |
| Educational Facilities     | -0.171                | **0.03**                 |         | 0–200 1.14      | 0.40             | ![Graph](educational_facilities.png) |
|                             |                       |                          |         | 200–500 1.23    | 0.43             |                               |
|                             |                       |                          |         | 500–1000 0.37   | 0.13             |                               |
|                             |                       |                          |         | 1000+ 0.09      | 0.03             |                               |
| Official Facilities        | -0.4275               | **0.08**                 |         | 0–200 1.77      | 0.45             | ![Graph](official_facilities.png) |
|                             |                       |                          |         | 200–500 1.07    | 0.27             |                               |
|                             |                       |                          |         | 500–1000 0.69   | 0.17             |                               |
|                             |                       |                          |         | 1000+ 0.42      | 0.11             |                               |

\[ I_{l} \ldots I_{r} = \text{Breaking points} \]

It can be evaluated that parcels close to the main transportation routes, the commercial center, health, education, and official institution facilities have high average FAR value. In contrast, distant parcels have low FAR values. A similar relationship was found in the case of accessibility to the decisions stipulated by the plan. However, contrary to expectations, the weight of the first-degree road connection points that will connect the study area to the surrounding settlements remained low. As the FAR values stipulated by the plan on the parcel increase, the current FAR values also
| Criteria         | Sub-criteria           | Correlation Coefficients | Weights | Breaking Points | FAR | Coefficients | Graphs (x-Break Points, y-FAR) |
|------------------|------------------------|--------------------------|---------|-----------------|-----|--------------|--------------------------------|
| Plan Decisions   | Planned FAR            | 0.488                    | 0.09    | 0               | 0.16| 0.02         | ![Planned FAR-FAR](chart)     |
|                  |                        |                          |         | 0.6             | 0.47| 0.05         |                                 |
|                  |                        |                          |         | 0.9             | 0.71| 0.07         |                                 |
|                  |                        |                          |         | 1.05            | 0.58| 0.06         |                                 |
|                  |                        |                          |         | 1.2             | 0.91| 0.09         |                                 |
|                  |                        |                          |         | 1.6             | 1.31| 0.13         |                                 |
|                  |                        |                          |         | 1.8             | 0.85| 0.08         |                                 |
|                  |                        |                          |         | 2               | 1.17| 0.11         |                                 |
|                  |                        |                          |         | 2.4             | 1.11| 0.11         |                                 |
|                  |                        |                          |         | 4               | 3.03| 0.29         |                                 |

| Plan Decisions   | Planned Land Use       | 0.5395                   | 0.10    | Residential     | 1.05| 0.26         | ![Planned Land Use-FAR](chart) |
|                  |                        |                          |         | Commercial      | 3.03| 0.74         |                                 |
| Criteria                      | Sub-Criteria          | Correlation Coefficients | Weights | Breaking Points | FAR Coefficients | Graphs (x-Break Points, y-FAR) |
|-------------------------------|-----------------------|--------------------------|---------|-----------------|------------------|--------------------------------|
| Built Environment             | Parcel Size           | −0.268                   | 0.05    | 0–200           | 2.1              | 0.21                            |
|                               |                       |                          |         | 200–400         | 1.3              | 0.13                            |
|                               |                       |                          |         | 400–600         | 1.05             | 0.10                            |
|                               |                       |                          |         | 600–800         | 1.33             | 0.13                            |
|                               |                       |                          |         | 800–1000        | 1.38             | 0.14                            |
|                               |                       |                          |         | 1000–1500       | 1.12             | 0.11                            |
|                               |                       |                          |         | 1500–2500       | 1.32             | 0.13                            |
|                               |                       |                          |         | 2500+           | 0.44             | 0.04                            |
| Average FAR in 50 m Neighborhood | 0.5015                | 0.10                     | 0       | 0–0.60          | 0.13             | 0.02                            |
|                               |                       |                          |         | 0.61–0.90       | 0.51             | 0.08                            |
|                               |                       |                          |         | 0.91–1.20       | 0.63             | 0.10                            |
|                               |                       |                          |         | 1.21–1.60       | 0.78             | 0.13                            |
|                               |                       |                          |         | 1.61–2.00       | 0.96             | 0.16                            |
|                               |                       |                          |         | 2.01–4.00       | 1.13             | 0.19                            |
|                               |                       |                          |         |                 | 1.36             | 0.32                            |
Table 5
Land prices and related statistics.

| Criteria      | Sub-Criteria      | Correlation Coefficients | Weights | Breaking Points | FAR | Graphs (x-Break Points, y-FAR) |
|---------------|-------------------|--------------------------|---------|-----------------|-----|------------------------------|
| Socioeconomic | Land Prices       | 0.48                     | 0.09    | 0–50            | 0.64| 0.07                         |
|               |                   |                          |         | 50–100           | 0.98| 0.11                         |
|               |                   |                          |         | 100–200          | 1.23| 0.14                         |
|               |                   |                          |         | 200–300          | 2.1 | 0.25                         |
|               |                   |                          |         | 300–400          | 3.59| 0.42                         |
increase. While the FAR values are higher in commercial areas, they are relatively lower in residential areas. Parallel to the land prices, FAR values increase as the land prices increase. Although there is a relatively weak relationship between parcel size and FAR values, small parcels have a higher FAR value than large parcels, and large parcels have a lower FAR value than small parcels. The relationship between the 50 m circular FAR value and the parcel’s FAR value is also directly related. If there is high-level construction in the neighborhood, it can be concluded that there is high-level construction on the parcel.

Model results, calibration and evaluation

Criteria affecting the distribution of FAR values across the study area of the Saray settlement are compiled as 15 sub-criteria under five main groups. Proximity to existing road connections and urban facilities, proximity to planned road connections and urban facilities, FAR values and land use decisions of the zoning plan, built environment, and socioeconomic criteria are the main groups. All parcels in the study area were evaluated using the weights and coefficients of the selected sub-criteria and breaking points determined in the previous stage. Tables 1–5 show the weights of sub-criteria and the coefficients of the breaking points.

The coefficients and weights for each parcel were combined by using the "Weighted Linear Combination Method." As a result, model coefficients showing the probable FAR value of each parcel were obtained. Model coefficients consist of values of 0.07 minimum and 0.4038 as the maximum. These values show the FAR value relationship of the parcels with respect to each other. In order to use these values as a FAR value, we go through a calibration process specific to the study area. During the calibration process, the thesis that there is a linear relationship between FAR values and the model values is accepted (Table 6). An equation is generated by equating the smallest model value obtained to the smallest current FAR value in the study area and the maximum model value obtained to the maximum available FAR value in the study area (Table 6). All model values are converted into FAR values by using this Eq. (4). The real FAR values and the modeled FAR values obtained from the calibration process are shown in Fig. 10.

\[ Y_a = 17.975x_a - 1.2582 \]  

(4)

\( Y_a \): FAR Value of Parcel a  
\( X_a \): the model value of parcel a

The parcels subject to change between 2012 and 2019 were taken into account to measure the calibrated model values’ accuracy. In the parcels with a current average FAR value of 0.04 in 2012 and a modeled FAR value of 1.64, the average FAR value in 2019 is 1.39. The remaining values can be followed from Table 7. When Fig. 11 and Table 7 are examined, it is seen that the model is quite successful in explaining the FAR values of the changed parcels.
### Table 6
Model results, 2019 FAR values, linear calibration function and scatter plot of dataset.

| Model Value | Model Value (Mean) | 2019 FAR (Mean) |
|-------------|--------------------|-----------------|
| 0.07–0.10   | 0.085              | 0.003           |
| 0.11–0.15   | 0.127              | 0.058           |
| 0.16–0.20   | 0.174              | 0.261           |
| 0.21–0.25   | 0.221              | 0.768           |
| 0.26–0.30   | 0.270              | 1.240           |
| 0.31–0.35   | 0.320              | 2.357           |
| 0.36–0.40   | 0.379              | 3.246           |

![Linear calibration function](image)

![Scatter plot](image)
Table 7
Comparison of 2012 and 2019 FAR values and model values.

| Model Summary | 2012 FAR (Mean) | Model Value (Mean) | 2019 FAR (Mean) | Increase (Mean) |
|---------------|-----------------|--------------------|-----------------|-----------------|
| 1.00–2.00     | 0.04            | 1.64               | 1.39            | 1.34            |
| 2.01–3.00     | 0.12            | 2.49               | 2.05            | 1.93            |
| 3.01–4.00     | 0.36            | 3.39               | 2.72            | 2.36            |
| 4.01–5.00     | 0.48            | 4.54               | 3.64            | 3.16            |
| 5.01–6.00     | 0.57            | 5.33               | 3.74            | 3.17            |

![Chart](image)

**Fig. 11.** Changed parcels between 2012 and 2019 and model values.

**Determining the type of growth demand**

In order to reveal the growth trends of the study area, the quantity and quality of the changes that took place between 2012 and 2019 were examined in total and across the city zones. Analyzing the changes in the previous period will give more realistic results to make future predictions. It is possible to examine the changes taking place in the urban area in two groups. In the first group, the increase of FAR value occurs on a parcel that has not been built up before (newly built-up). In the second group, the FAR value increases with the transformation of the existing buildings (transformation). Simultaneously, the city was divided into four zones by considering the distribution of the FAR values in the neighborhood of 100 m. The amount and types of change for each region were analyzed separately (Fig. 12 and Table 8). Accordingly, 24% of the total change took place in the central zone, 52% in the mid-central zone, and 24% in the middle zone. While newly built-up parcels are mostly in the central and middle zone, the transformation rate is higher in the mid-central zone.

**Determining the amount of growth demand**

The demand for total construction area in urban space, therefore, to FAR values, consists of many variables, primarily the population size. Variables such as household size, household income, family structure and habits, and secondary housing affect the amount of construction area per person and thus the FAR values. In this study, the demand was evaluated as linear with the population size. The demand for total construction area and total FAR values, parallel with the population change between 2012 and 2019, was evaluated. It was assumed that this trend would continue for the years 2030 and 2040. The population amount in 2030 and 2040 was calculated as a linear function product, taking into account the population data for every five years since the 1980s. Accordingly, it was assumed that the study area’s population size would be 32,336 in 2030 and 37,002 in 2040 (Fig. 13). The total...
| Zone          | Newly Built-Up | Transformation | Total |
|--------------|----------------|---------------|-------|
|              | Count | Mean Change Amount (FAR) | Total Change Amount (FAR) | Count | Mean Change Amount (FAR) | Total Change Amount (FAR) | Count | Mean Change Amount (FAR) | Total Change Amount (FAR) | Change Amount (Ratio) |
| Central Zone | 28    | 3.17 | 88.85 | 19 | 2.32 | 44.13 | 47 | 2.83 | 132.99 | 0.24 |
| Ratio        | 0.67  |       |       | 0.33 |       |       |       |       |       |       |
| Mid-Central Zone | 66 | 2.24 | 148.00 | 66 | 2.06 | 135.64 | 132 | 2.15 | 283.64 | 0.52 |
| Ratio        | 0.52  |       |       | 0.48 |       |       |       |       |       |       |
| Middle Zone  | 73    | 1.29 | 94.34 | 16 | 2.12 | 33.93 | 89 | 1.44 | 128.27 | 0.24 |
| Ratio        | 0.74  |       |       | 0.26 |       |       |       |       |       |       |
| Total Ratio  | 167   | 0.61 | 332.39 | 101 | 0.39 | 214.51 | 268 | 1.00 | 544.90 | 1.00 |

Table 8
Transformations and newly built-ups between 2012 and 2019 across the urban zones and related statistics.
amount of demand for the whole urban area and urban zones was determined (Table 9). Accordingly, while there is a need for a construction area of 430,767 m² (841 units of FAR value) in addition to the total construction area of 2019 for 2030, 391,606 m² (765 units of FAR value) is needed for 2040 in addition to the total construction area of 2030 (Table 10). The total amount of FAR value need for 2040 is less than the total amount of FAR value need for 2030 because the horizontal growth rate of the urban area is higher than the vertical growth rate. In the simulation phase, the demand amounts determined for the urban zones were met.

**Simulation**

Finally, simulations for 2030 and 2040 were created using the calibrated model FAR values and the growth trends between 2012 and 2019. The model assumes that the population growth rate, increase
### Table 9
Urban growth by years and demand scenarios for 2030 and 2040.

| Year                  | Population | Total Parcel Area (m²) | Mean Parcel Area (m²) | Parcel Area per Person (m²) | Total Construction Area (m²) | Mean Construction Area per Parcel (m²) | Mean Construction Area per Person (m²) | Total Floor Area Ratio |
|-----------------------|------------|------------------------|-----------------------|----------------------------|------------------------------|----------------------------------------|----------------------------------------|------------------------|
| **Ground Truth**      |            |                        |                       |                            |                              |                                        |                                        |                        |
| 2012                  | 23,938     | 1,233,517              | 418.28                | 51.53                      | 1,313,738                    | 445.49                                 | 54.88                                  | 3470                   |
| 2019                  | 27,204     | 1,313,742              | 421.75                | 48.29                      | 1,587,862                    | 509.75                                 | 58.37                                  | 4005                   |
| 7 Years Increase      | 3266       | 80,226                 | 3.46                  | −3.24                      | 274,124                      | 64.26                                  | 3.49                                   | 535                    |
| Increase Amount by Year | 1 Year  | 467                    | 11,461                | 0.49                       | 39,161                       | 9.18                                   | 0.50                                   | 76                     |
| **2030 Scenario - Current Trend Continues** |            |                        |                       |                            |                              |                                        |                                        |                        |
| Need                  | 32,336     | 1,439,811              | 427.19                | 43.20                      | 2,018,629                    | 610.73                                 | 63.85                                  | 4846                   |
| 2040 Need             | 37,002     | 1,554,419              | 432.14                | 38.58                      | 2,410,235                    | 702.53                                 | 68.83                                  | 5611                   |
|                       |            |                        |                       |                            |                              |                                        |                                        |                        |
in FAR values, and growth trends based on zones will continue as is. As a result of the model, it is estimated that the FAR values in the settlement will be higher in the city center and decrease from the city center towards the periphery. Besides, parcels close to the main transportation routes will take relatively higher FAR values than the urban periphery (Fig. 14).

Discussion and conclusion

This study aims to estimate the FAR values, one of the most critical factors that shape the urban fabric, by using the relevant criteria. By taking advantage of cellular automata and GIS, cadastral parcels, which are the smallest unit where change occurs in urban space, were used in the study. Parcels with functions such as urban green areas, urban facilities, military areas, industrial areas, whose use of FAR is determined according to a particular need, are not included in the model. Similarly, the parcels owned by public authorities or whose ownership is foreseen to be taken over by the public authorities in the future in line with the zoning plan decisions are also excluded from the study. The purpose of the study is to determine the possible FAR values of the parcels that are subject to residential and commercial use.

The most important feature of the designed model is estimating the FAR values that affect the urban fabric in the whole city on a temporal and parcel scale. The difference of the proposed model from the urban growth models in the literature is that vertical growth is also taken into account as well as horizontal growth, and it aims to estimate the FAR values for all parcels. Concurrently, the model’s criteria were determined and weighted by taking into account the current growth trends of the study area. This feature of the model increases the applicability for different urban areas. Model results show the possible construction area that can be located on the parcel. Model outputs are expected to guide urban planners and city managers in the decision-making process. The predicted FAR values also allow us to analyze the factors affecting microclimate, such as shadows, heat island formation, building orientation, and visibility before they occur. It is possible to predict the urban texture according to different demand scenarios by using the model results.

Household size, household income, social clustering, and other socioeconomic criteria could not be included in the model since socioeconomic variables are not spatially kept on the neighborhood scale in the study area. The results obtained from the model can be evaluated together with the FAR values of the parcels not included in the model. Land use status and decisions for all parcels and interactions between each other can be considered as possible model additions that should be discussed in future.
studies. On the other hand, high resolution geospatial data for more time periods will strengthen the model results. The chosen study area is a small-medium sized urban area with a single city center. The proposed model can have higher capability by using geospatial socioeconomic data and more time period in a multi-core city.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

None.

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