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Planned vs. Real City: 3D GIS for Analyzing the Transformation of Urban Morphology

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Abstract

Cities are constantly evolving: buildings are built and demolished, altering the landscape of our cities; Urban Plans describe what we want our cities to be, undergoing revisions as we change our vision of the future of our cities. This paper presents a methodology to model the interactions between what the city is and what it wants to become. The old quarter of Sant Andreu in Barcelona (Spain) was used in a pilot study for the development of a methodology to automatically quantify and visualize the outcome of regulation changes as a strategic tool for the Urban Planning Department of the Barcelona City Council. This paper describes a methodology developed to measure the magnitude of the buildings conformity or disconformity to the determinations of the Urban Plan (current and proposed), and to display this information in 3D, to allow a more natural interpretation of the results. Special care was put into the methodological approach to ensure that it could be replicated at neighbourhood or city-wide scales. A methodology for the interpretation of the heights of staircase towers and ventilation courtyards from neighbouring entities heights, through the analysis of adjacency relationships in a non-topological Geographic Information System is also discussed.

Keywords: 3D GIS, Urban planning, Urban regeneration, Local management, Smart visualization, Topology

1 Introduction

Urban processes driven by changing social, economic and environmental factors must be rethought [1, 2]. The development of the cities of the future does not necessarily need to be the sprawling growth of past decades but the regeneration of existing urban spaces [3]. Technology can help understand these processes and allow policymakers to make better decisions [4] with deeper public participation [5] for more adaptable, dependable and liveable cities [6].

In the consolidated city and in particular its historic centre, the complexity of the urban pattern makes the regeneration processes (both physical and social) a difficult task; nonetheless, these are usually the areas with a more pressing need for urban renewal processes [7].

Transformation processes in these settings must handle information about the morphology of the built environment with a sensitivity that considers urban quality, sustainability and security, while giving response to the needs of its inhabitants [8].

In areas undergoing regeneration processes, planners need to know with precision both past and present state of the city to plan for a better future. With this objective, a strategic tool was developed to aid in the decision-making process, using the vast pool of urban data stored in cadastral and planning databases to (a) accurately quantify the conformity with height regulations of today's built environment and (b) to evaluate the outcomes of modifications of height regulations.

The object of this paper is to explain the methodology developed to precisely quantify the complex interactions between built reality and urban regulations.

1.1 Case of study

The case of study chosen for the development of the methodology was the old quarter of the Sant Andreu District in Barcelona.

The buildings in the area of study (Figure 1) are part of the centre of the former town of Sant Andreu, from which the district takes its name, and the development it underwent in the 19th century when it was incorporated to Barcelona. This historic development resulted in a complex urban structure suitable to use as workbench to test the methodology, with an area of 90 hectare containing 2,775 parcels, distributed in 148 city blocks around its main commercial street, *Gran de Sant Andreu*.

The area of study was in the process of modifying the planning regulations [9] in effect since 1976 in 27 municipalities of the Barcelona Metropolitan Area. Being a plan from 1976, some parameters such as the maximum height were not drawn explicitly in the planning regulations, and had to be interpreted [10] with the aid of the staff in the Urban Studies Bureau of the Urban Planning Department of the Barcelona City Council.

The case of study was chosen because of the interest the city planners had in knowing with precision the compliance of the buildings in the area with the maximum heights allowed by the planning regulations.

The methodology developed was very valuable to evaluate the possible outcomes of modifications of different parameters of the regulations, and made possible to assess the current built mass of the whole city.

2 Methodology

2.1 Interpretation of the height of ventilation courtyards and staircase towers

The height of buildings was stored as 2.5D cartography in a sub-parcel dataset (being sub-parcels pieces within a parcel with a distinct height from neighbouring sub-parcels). Height information was stored as an alphanumeric string which encoded several pieces of information about the sub-parcel, including the number of floors below and above street level. For example, a sub-parcel with a "–II+V" attribute had two subterranean floors and five floors above street level.

In the case of ventilation courtyards (VC) and staircase towers (ST), sub-parcels did not have a height attribute but a code that identified them as such ("P" for VC and "E" for ST). However, ST volumes protrude from flat roofs and VC are considered by planning regulations as part of the building, and consequently both types needed to be assigned a height value.

Since VC accounted for almost 20% of the area of all sub-parcels and ST for another 2%, to get accurate results a methodology had to be developed to automatically assign height values to this types of entities from their spatial context, considering that ST are as high as the top floor they serve in their parcel and VC have a lightweight roof at the level of the lowest floor they serve in their parcel.

For sub-parcels representing ST, the assigned value was the maximum height of all adjacent sub-parcels belonging to the same parcel (Figure 2) and for sub-parcels representing VC, the assigned value was the lowest height of all adjacent sub-parcels belonging to the same parcel (Figure 3).

The calculation of the height to be assigned to ST and VC involved two topological relationships: (a) adjacency to other polygons but (b) considering only polygons inside the same parcel. Since the Geographic Information System (GIS) used was non-topological, a methodology had to be implemented in Structured Query Language (SQL):

1) A tool to convert lines to polygons was used to get a table with 3 ID fields: line ID, left polygon ID and right polygon ID (*lines*) for all sub-parcels (*volumes*).
2) A dictionary of key-value pairs (*type_dictionary*) was made to translate the alphanumeric encoding to a numeric value (*volumes_height*) measuring the number of floors above street level (Figure 4, above).
3) A table with the attributes of the polygons on both sides of each line was built (*lines_volumes*) from the tables described previously (Figure 4, below).
4) This intermediate table had to be reshaped as a list using union queries, excluding the polygons not pertaining to the parcel the fragment belonged to and excluding the sub-parcels that were not ST (figure 5, left) or VC (Figure 5, right).
5) An aggregation query for each type was performed to get the corresponding values of the height attribute: the highest value of all neighbours for ST and the lowest value of all neighbours for VC.

Figure 1: Area of study in the Sant Andreu District of Barcelona

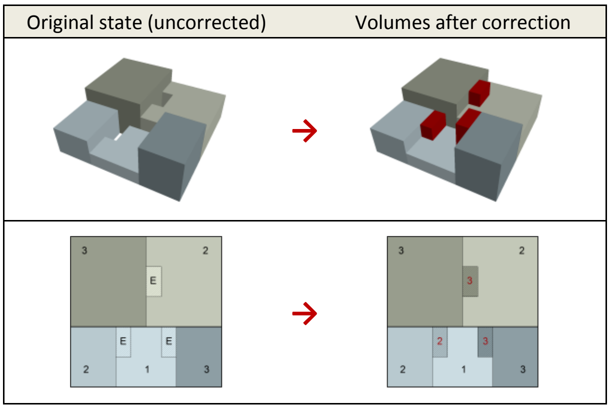


Figure 2: Correction of staircase towers (red) of two neighbouring parcels (sub-parcels in brown and blue hues)

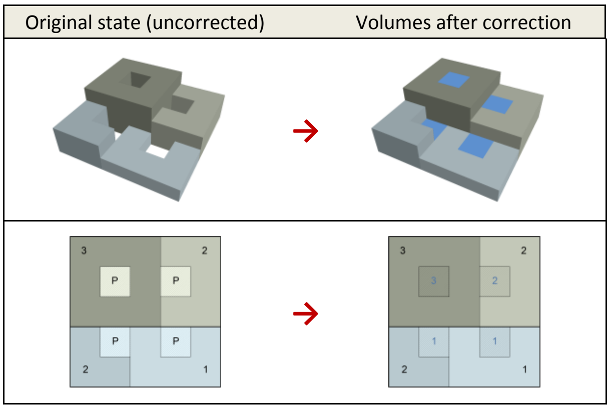


Figure 3: Correction of ventilation courtyards (blue) of two neighbouring parcels (sub-parcels in brown and blue hues)

2.2 Overlay operations

With the sub-parcels volumes corrected and their height converted to a numeric value, their heights were compared to the height the plan allowed using two Boolean spatial operations: (a) a spatial intersection (Figure 6, left), the result of which was the fragments of sub-parcel inside zones and (b) a spatial difference (Figure 6, right), the result of which was the fragments of sub-parcel inside systems (roads and parks).

With the result of the overlay operations it was possible to determine the conformity to the urban plan for each of the fragments (Table 1) from their building height (HB) and planned height (HP).

The magnitude of the conformity (measured in area units) for each resulting sub-parcel fragment was represented in a map, multiplying its area by the corresponding number of floors beneath or exceeding the allowed height (Figure 7). This map was a very valuable analytical tool, but to visualize its information in a more intuitive way a different approach had to be developed to make it easier to interpret.

Table 1: Types of fragments from the overlay operations

Fragment	Plan entity	Condition	Operation	Symbology
Underbuilt	Zones	HB - HP < 0	Intersection	Blue hues
Conformant	Zones	HB = HP	Intersection	Grey
Overbuilt	Zones	HB - HP > 0	Intersection	Pink hues
Overbuilt	Systems	HB > 0	Difference	Dark green
Conformant	Systems	HB = 0	Difference	Light green

2.3 Aggregation at parcel level

It is not legally allowed to compensate overbuilt volumes with underbuilt ones inside a parcel (Figure 8), and accordingly aggregate calculations had to be performed separately for both situations to avoid the aggregate operations adding positive and negative numbers (which would be mathematically correct but not possible according to the regulations).

Formulae 1 to 5 show the aggregation operations to calculate for each parcel: the total built area (1), the maximum allowed built area in zones (2), the overbuilt area in zones (3), the underbuilt area in zones (4), and the overbuilt area in systems (5).

$$Real\ Built\ Area_{Parc} = \sum_{Subp \in Parc} HB_{Subp} \cdot A_{Subp} \quad (1)$$

$$Allowed\ Built\ Area_{Parc} = \sum_{FragZ \in Parc} HP_{FragZ} \cdot A_{FragZ} \quad (2)$$

$$Overbuilt_{Parc} = \sum_{FragZ \in Parc} (HB_{FragZ} - HP_{FragZ}) \cdot A_{FragZ} \quad (3)$$

$$Underbuilt_{Parc} = \sum_{FragZ \in Parc} |HB_{FragZ} - HP_{FragZ}| \cdot A_{FragZ} \quad (4)$$

$$Overbuilt\ in\ Systems_{Parc} = \sum_{FragS \in Parc} HB_{FragS} \cdot A_{FragS} \quad (5)$$

Figure 4: Queries to build the neighbours attributes table

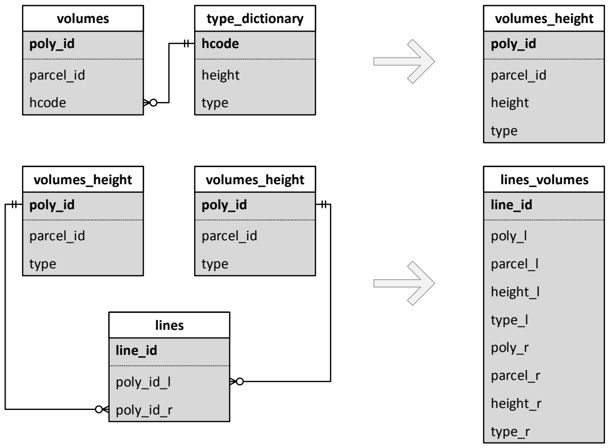


Figure 5: Operations to obtain all neighbouring volumes inside the same parcel for every ST (left) and VC (right)

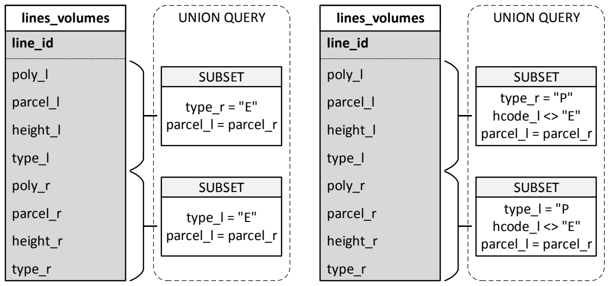


Figure 6: Spatial intersection (left) and difference (right)

Figure 7: Conformity to the urban plan of each fragment

Using the following notation:

- **HB**: Real height of the building, measured in number of floors above street level.
- **HP**: Maximum height according to the plan, measured in number of floors above street level.
- **A**: Area of a polygon entity (surface of land occupied).
- **Parc**: Set of parcels inside the area of study.
- **Subp**: Set of sub-parcels.
- **FragZ**: Set of fragments from the spatial intersection between parcel and planning layers (in zones).
- **FragS**: Set of fragments from the spatial difference between parcel and planning layers (in systems).

3 Results

3.1 Parcel level results

The aggregated values were displayed in choropleth maps, to visualize the magnitudes of overbuilt and underbuilt areas of each parcel. These maps were a strategic tool for the City Planning Department to visualize and identify the parcels with the most outstanding values.

With the map of overbuilt areas of parcels (Figure 9), planners were able to identify the parcels with a higher degree of excess volume and to visualize the spatial clustering of overbuilt parcels facing certain streets or concentrated in specific city blocks.

The map of underbuilt areas in parcels (Figure 10) allowed planners to visualize the places where underbuilt parcels were clustered together as candidates to successfully implement transformation policies.

3.2 A new approach for the representation of fragment level results in 3D

The representation of the results using 2D maps was unable to convey the complex volumetric information successfully because height data had to be abstracted to be represented in plan view as colour scales, hatch densities or labels.

The use of 3D imagery allowed the authors to represent the volumes in a more natural and intuitive way since it matched the way we experience our cities.

Figure 11 shows the criteria to display the overlapping information of overbuilt and underbuilt fragments. The third dimension allowed the authors to display overlapping information without having to resort to 2D representation constructs such as transparency or hatching.

Figure 12 shows the results for the case of study, where the viewer is able to visualize and relate two concepts simultaneously (real height and planned height) much more easily than using 2D maps.

An axonometric aerial photograph was compared to the corresponding result (Figure 13) to highlight the value of the methodology developed as an analysis and visualization tool. In the 3D synthetic image the differences between built reality and planned city are more apparent and easier to interpret.

Figure 8: Parcel with overbuilt and underbuilt fragments

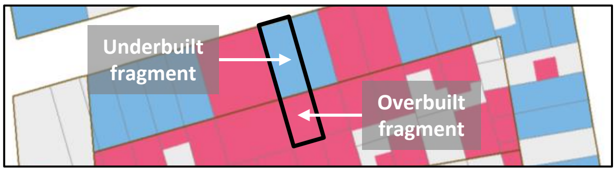


Figure 9: Overbuilt aggregated area in parcels

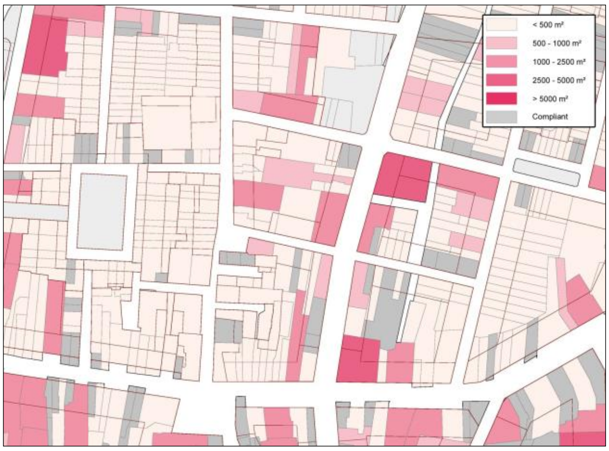


Figure 10: Underbuilt aggregated area in parcels

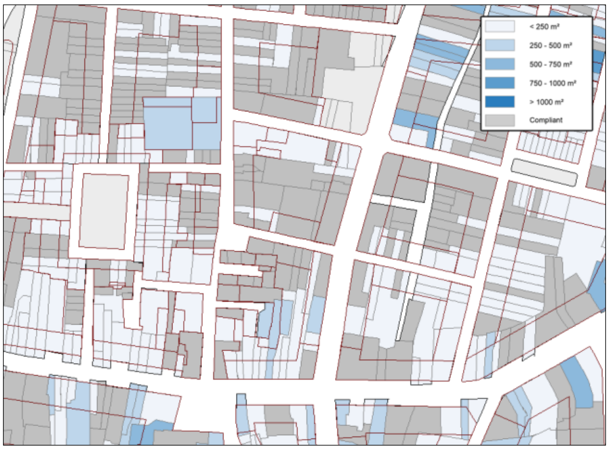


Figure 11: Height interpretation in the 3D model

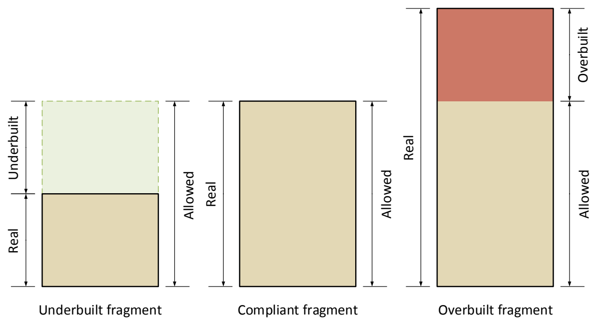


Figure 12: Volumetric analysis of overbuilt (red) and underbuilt (green) fragments in the case of study

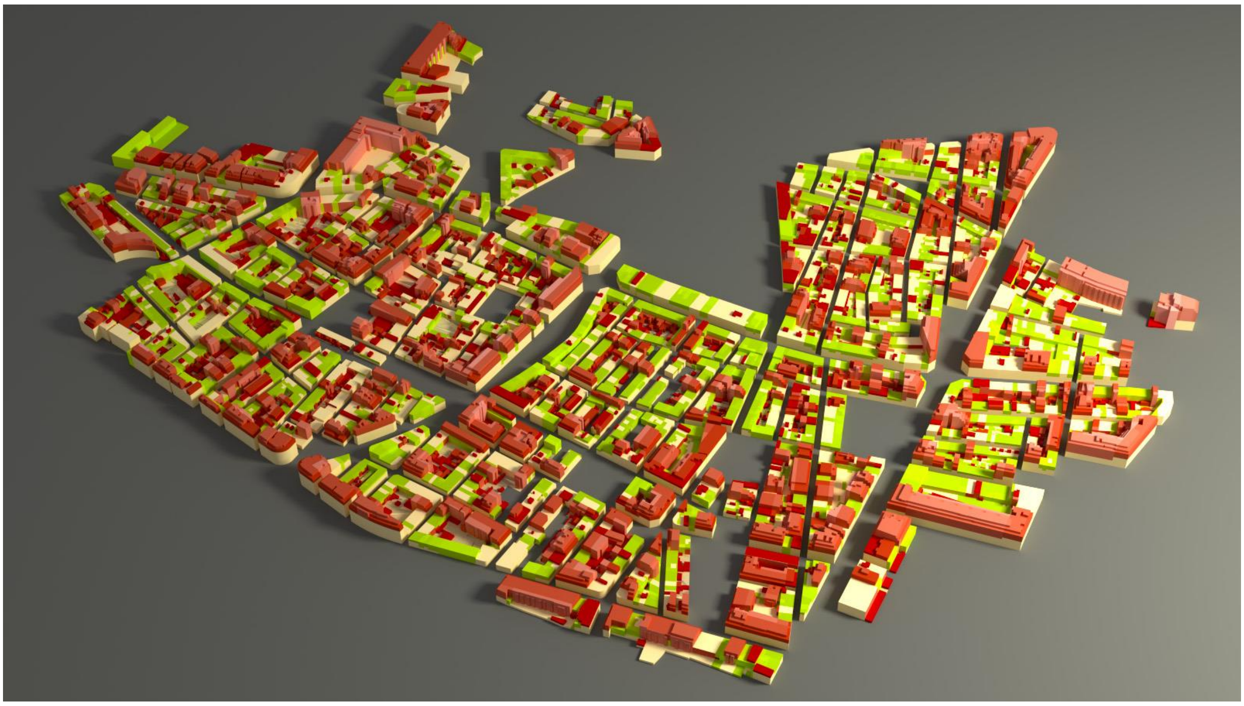
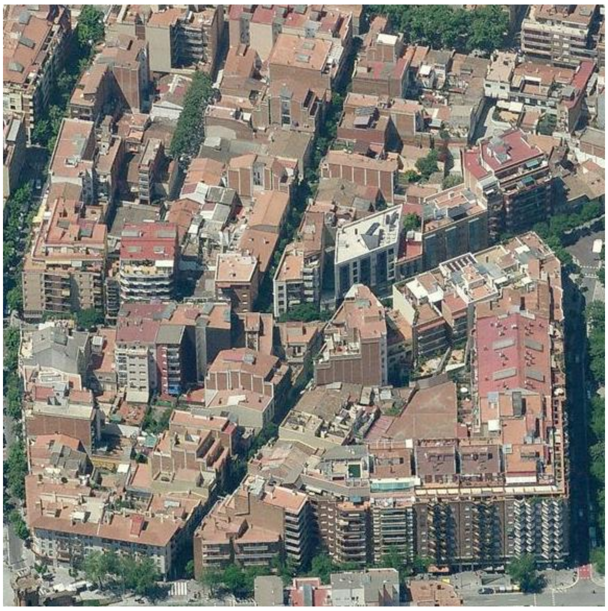
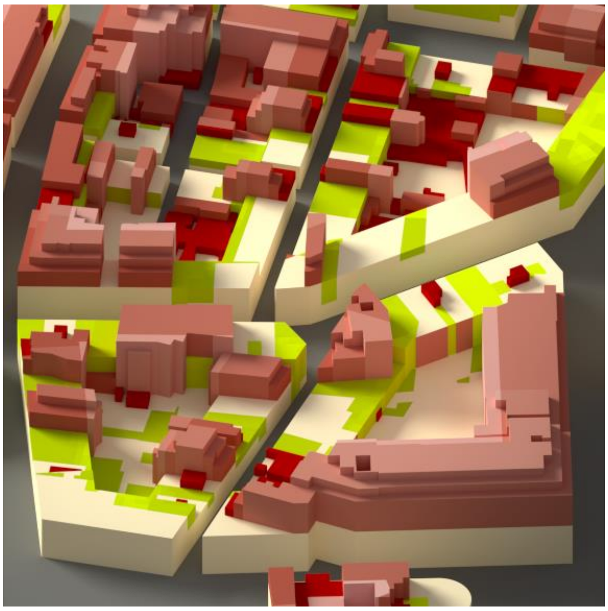


Figure 13: Aerial axonometric view and 3D representation of the same area



Source: Bing Maps



3.3 Quantification of the outcomes of proposed changes in regulations

In addition to the visualization of the morphological differences between the proposed city and the real built environment, the methodology allowed planners to precisely quantify the outcomes of proposed regulation changes.

Figure 14 shows an example of a proposed regulation change, where two additional floors could be allowed in part of a city block. The methodology allowed decision-makers to measure the additional built area that would become compliant with the new regulation and the number of properties that would change its legal status.

4 Conclusions

The presented methodological approach seeks to assist in implementing better policies in urban transformation processes, with better and easier to understand information, making possible to measure and visualize with precision the conformity of the built environment to the determinations of Urban Plan, and to evaluate the outcome of proposed regulation changes.

The 3D visualization techniques allow the discovery of patterns not obvious even for trained professionals and is a valuable tool to communicate the results of the analysis.

To improve the accuracy of the analysis, a methodology to study adjacency relations in a non-topological GIS was developed using SQL, which allowed assigning height values to entities that didn't have this attribute from their spatial context.

As further investigations, an improvement of the methodology is proposed to incorporate information about building quality, economic activity and demographic information in densification processes to be able to:

- Determine which parcels are more likely to be transformed according to their age, uses, habitability, economic value, etc.
- Estimate the potential number of people affected by and/or benefited from regulation changes.
- Calculate the taxation of the increased value of the properties in redevelopment scenarios.
- Prioritize zones with greater incompliance and/or obsolete typologies (such as outdated industries) to be included in transformation processes.
- Explain the possible historic reasons that have resulted in the current morphology of the city.

Furthermore, to improve the accuracy and usefulness of the visualization of the results it is proposed:

- The incorporation of a Digital Elevation Model (DEM) in the 3D model.
- The use of Augmented Reality tools to visualize the results on site.

Acknowledgements

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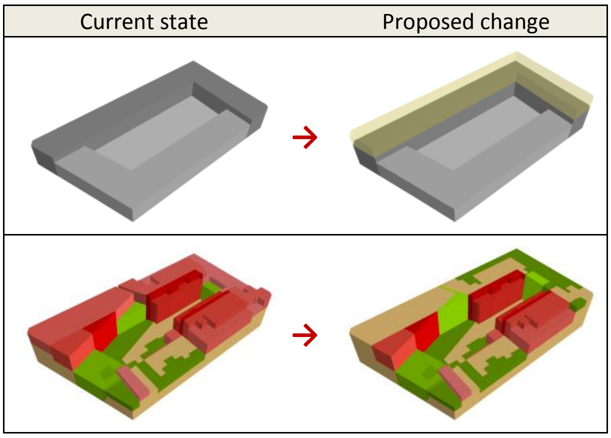
Figure 14: Proposed increased allowed height in a city block (above) and resulting outcome (below)



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