Computational Approach for the Assessment of Transit Oriented Development Principles

A multivariate optimization method for urban planning

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This paper presents a computational approach to provide dynamic assessment and optimization of principles derived from Transit Oriented Development (TOD) - an urban development model that advocates compact, walkable, and mixed-use neighborhoods, centered around transport stations. In spite of being increasingly promoted in several cities of the world, TOD lacks an approach that addresses multivariate data for optimization of its principles. In this paper, we propose a methodology backed by an algorithmic-parametric CAD environment, applied to a neighborhood unit in a case study. The objective is the analysis and improvement of TOD relevant and measurable features (transit accessibility, walkability and diversity) in order to optimize neighborhoods' features. The ultimate goal is to facilitate the management of solutions in TOD planning processes, supported by a principle-index-tool approach triad.

Keywords: Transit Oriented Development, Multi-objective optimization, Computational urban planning,

INTRODUCTION

According to Global Fuel Economy Initiative [1], fuel combustion in motor vehicles is responsible for up to 75 percent of urban air pollution, while World Health Organization [2] associates outdoor air pollution with 3.7 million premature deaths in 2012. Besides contributing to carbon emissions, the adopted logic of organizing cities is responsible for great inconveniences in contemporary urban centers (e.g. automobile dependence, fragmented spatial patterns, less social interactions). Transit Oriented Development (TOD) is an urban development model that became one of the key planning paradigms aimed at creating compact, walkable, mixed-use communities, centered around high quality transport systems. TOD facilitates the creation of vibrant livable communities without depending on an automobile for mobility, and it is being increasingly promoted in several cities of the world as a sustainable policy (Calthorpe 1993; Vale 2015). Nevertheless, although there is no
universally accepted definition of TOD, it is often described in a physical manner: an area of compact mixed-use buildings served by a multimodal mobility network within walkable distance (Cervero & Kockelman 1997; Calthorpe & Fulton 2001; Suzuki et al 2013; Vale 2015). In this logic, basic urban needs are easily accessible without demanding automobiles or spending large amounts of commuting time, with the intention of supporting more autonomous and sustainable neighborhoods.

TOD is characterized by a few main features: proximity to transport stations and a functional relationship with them, as well as compact, mixed-use neighborhoods that encourage walking, cycling, and the use of public transit by residents, employees, shoppers and visitors. In other words, it should encourage the use of public transportation by creating neighborhoods with compact urbanization, diversity in land use and urban design geared to the pedestrian - where one can walk to the stations and other amenities. The primary principles of TOD consist of: (i) transit accessibility - locating amenities, employment, retail shops and housing around transit hubs; (ii) walkability - the ability that a particular neighborhood has to connect housing and amenities points through distances that can be traveled on foot; (iii) diversity - providing a mix of uses, densities and housing types in the same district; (iv) density for mass transit - encouraging infill and redevelopment along transit corridors within existing neighborhoods, allowing the system to run efficiently (Cervero & Kockelman 1997; Calthorpe & Fulton 2001; Dittmar & Ohland 2004; Suzuki et al 2013).

According to Dittmar et al (2004), there have not been sufficiently developed standards or systems to help the actors involved in the process of bringing successful TOD projects into existence. On the other hand, TOD is a multi-variable dependent system, as long as it relies on measurable parameters for improved performance. It also considers geometric principles and objective features for designing autonomous neighborhoods. In other words, it represents a kind of complex proposition, derived from some variables considered as crucial in achieving its objectives, what makes TOD a potential case for computational implementation (Lima et al 2016).

This study advocates a computational urban planning approach for evaluation and optimization of TOD features supported by a triad principle-index-tool. That is, for each addressed TOD principle, there is a corresponding index and a calculation algorithm that makes it possible to objectively quantify and, therefore, optimize alternatives for urban configurations for a TOD oriented area. In this sense, this approach proposes the application of the following tools: (i) Station Proximity Calculator (SPC) - a computational tool that measures the Station Proximity index (SPI) of one or more locations. SPI is an indicator that calculates the smaller physical path between a transport station and one (or all) plot(s) in a neighborhood, aiming to assess the Transit accessibility of a particular plot or whole district; (ii) Walk Index Calculator (WIC) - an algorithm that makes it possible to measure the Walk Index (WI), an indicator intended to assess the walkability of a particular location using three parameters related to physical distances: proximity, diversity and variety; (iii) Mixed-use index calculator (MXIC) - a tool for measuring the Mixed-use index (MXI) of an area. Proposed by Hoek (2008), this indicator computes the ratio between residential and non-residential areas in a location, in order to analyze the diversity of a neighborhood. These three calculators (SPC, WIC and MXIC) are intended to support planning strategies as long as they dynamically assess their respective indexes (SPI, WI and MXI), which, in turn, are intended to measure their respective TOD principles (transit accessibility, walkability and diversity).

In this context, this paper presents an approach that advocates the application of the aforementioned calculators in optimization tasks that seeks to improve: (a) the positioning of a transport station, aiming at improved transit accessibility (smaller physical distances to transport nodes); (b) the location/distribution of amenities, intending to minimize commuting distances and provide greater walkabil-
ity, and; (c) the balance of living and working places, aiming at a greater diversity. Besides, we propose the assessment of Spacematrix density indicators, proposed by Pont & Haupt (2010), for supporting the goals definitions and the decision making process.

**METHODOLOGICAL APPROACH**

The presented approach searches for a set of tools to assist on TOD oriented planning processes, and is not intended to act as an independent-automatic solver. It is also not intended here, to develop a system that includes all the variables involved in the various aspects of TOD, but to develop a set of computational tools that supports decision making processes, providing instruments that manage data and perform complex calculations. The tools themselves do not provide a better city, but are intended to allow the crossing of relevant information, providing decisions supported by data obtained in a more efficient way than traditional means. The role of the actors involved in urban development processes remains central, and it’s still them that will stipulate goals, feed the system and consider subjective and "non-programmable" aspects, such as economic and social dynamics, among others.

Geometric entities were associated with urban elements, in the construction of the parametric model, according to the following criteria: (a) points represented the location of buildings and referred to different urban functions (e. g. living, educational, retail, food, recreational); (b) curves simulated the existing network of streets, and; (c) polygons were used to play the role of buildings. Those entities are intended to cast as input for the aforementioned tools and resources, explained in more detail in sequence:

**Station Proximity Calculator (SPC)**

This tool is directly related with Transit Accessibility issues, as long as it intends to measure the distance between a transport station and one (or all) plot(s) in a neighborhood. In this regard, the proposed algorithm calculates the path(s) with smaller physical distance(s) between a station and one (or all) destination(s) in a district, considering slope(s) in the path(s). The score decreases as the distance approaches 1.6 km (20 min walk) and a 0 index is awarded for distances greater than 1.6 km (see table 1). The algorithm also applies a penalty factor (according to the acclivity) for estimating a score to classify the proximity to the station. For instance, in relation to a particular locality, if a station is 0.4 km away (5 min walk), then the maximum index (1) is assigned for this plot. If the station is a 1 km away from a particular plot, but with a 10% acclivity, then a 10% penalty is applied. It establishes a simple relationship to differentiate paths accordingly to their acclivity, but as long as it works on a parametric environment, it is possible to adopt other criteria for penalization.

**Walk Index Calculator (WIC)**

This algorithm works in a similar way of Station Proximity Calculator. However, it is intended to estimate objective features of walkability from a location. It adapts some criteria from Walkscore Index [3], for measuring three features (proximity, diversity and variety) from seven categories of amenities (educational, commercial, food, recreational, entertainment, health and services) in order to assign three complementary walk indexes to a particular location. Proximity Index (PI) considers the smallest path (distance and declivity) for the nearest amenity of a category, and uses the same criteria of SPC for assigning an index to a place. Diversity Index (DI) is intended to measure the average score from all amenities in a category near to this same place, while Variety Index (VI) expresses the number of amenities within a radius of 1,6 km away from one (or all) plot(s) in a category. In this sense, while PI gives us a hint of how close one location is to a particular amenity, DI is important to evaluate its average distance from all amenities, and VI gives an overall scenario of how many amenities are connected to a place by walking. These three features are meant to be analyzed together, in order to get a clearer comprehension of the walkability from a given plot or a whole area. In this sense, WIC gives three partial indexes from
seven categories. Each category has the same weight for estimating PI, DI and VI global indexes - points are summed and normalized to produce PI (from 0-1) and DI (from 0-1) scores. VI depends on the number of amenities of a district. Therefore, the greater these indexes are, the better the walkability of the analyzed area.

**Mixed-use Calculator (MXIC)**

This algorithm seeks to objectively measure a district diversity. It is based on the Mixed-use index (MXI) advocated by Hoek (2008), that calculates the sum of all residential and non-residential areas in a location, performing a comparison of their ratio in a given neighborhood, as demonstrated in Table 2. In this context, this tool makes it possible to quantify the distribution of residential and non-residential buildings. The closer the relationship between them is to 50/50, the better diversity a district has.

**Spacematrix Indicators Calculator (SIC)**

This set of algorithms is intended to calculate the Spacematrix density indicators proposed by Pont & Haupt (2010). Spacematrix concept advocates a multivariate density measuring approach that consists of three fundamental indicators: intensity (FSI), coverage (GSI) and network density (N). FSI reflects the building intensity, GSI demonstrates the relationship between built and non-built space, and N refers to the concentration of networks in a fabric. Spacematrix Indicators Calculators (SIC) evaluate density features of an urban area and are important to provide assessment of density issues (in this particular case on district aggregation) for a TOD oriented Neighborhood.

**Multi-objective optimization**

A Multi-Objective Optimization manages a set of objective functions to be optimized (maximized or minimized). It is a supporting tool for multiple criteria decision making, concerned with mathematical optimization of problems that involve more than one objective to be simultaneously satisfied. Usually, in multi-objective optimization problems, there is not a single solution that simultaneously optimizes each objective. In that case, the objective functions are said to be conflicting, and there is a number of Pareto optimal solutions. A solution is called Pareto optimal, or non-dominated, if none of the objective functions can be improved in value without decreasing some of the other objective values. As long as there is no additional subjective preference information, all Pareto optimal solutions are considered equally good.

Multi-objective optimization can be applied in many situations, where optimal decisions need to be taken while facing trade-offs between two or more conflicting objectives. In the context of proposed methodology, multi-objective optimizations are essential for achieving solutions involving conflicting objectives related to the aforementioned indexes and indicators.

<table>
<thead>
<tr>
<th>Proximity value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Excellent proximity - less than 5-minute walk</td>
</tr>
<tr>
<td>0.5</td>
<td>Good proximity - 10-minute walk</td>
</tr>
<tr>
<td>0</td>
<td>Disregarded proximity - more than 20-minute walk</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MXI value</th>
<th>0</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meaning</td>
<td>No house present</td>
<td>50/50 balance</td>
<td>100% residential use</td>
</tr>
<tr>
<td>District Type</td>
<td>Single use</td>
<td>Mixed-use</td>
<td>Single use</td>
</tr>
<tr>
<td>Examples</td>
<td>Office Park</td>
<td>City Center</td>
<td>Newtown</td>
</tr>
<tr>
<td></td>
<td>Factory Complex</td>
<td>Semi Central</td>
<td>Suburbia</td>
</tr>
</tbody>
</table>

Table 1
Reference values for proximity (and diversity). This indicators also apply for SPC.

Table 2
Meaning of the MXI (Hoek 2008).
**Approach workflow**

This approach relies on a logic of identification, evaluation and optimization of relevant TOD features, aiming at an efficient support approach for TOD oriented planning processes. Within this framework, we create a Rhinoceros/Grasshopper parametric model of the selected neighborhood to manage geometric and measurable features related to TOD principles. Octopus, a Grasshopper plug-in for applying evolutionary principles to problem solving, was used in order to search for many goals at once, as long as produces a range of optimized trade-off solutions between the extremes of each goal. Hence, the aforementioned tools use district data, emulated by geometric entities, as input for the formulation of a sequence of algorithmic operations, as follows: Firstly, the measurement of Station Proximity Index, Walk Index (proximity, diversity and variety), Mixed-use index and Spacematrix indicators, for each one of the plots (when applicable) or for the entire neighborhood, identifying demands for intervention, according to the standard indexes; Secondly, the improvement of station proximity index, given that optimization tasks allow one to identify which positioning for the station promotes the smaller average distance from all plots, providing better Transit Accessibility; Thirdly, the increase of amenities proximity, diversity and variety indexes, as long as multi-objective optimization enables one to identify where new amenities should be inserted, simultaneously considering these three indexes for each Walk Index category, providing a larger Walk Index and, consequently, suggesting a greater walkability; Fourthly, the evaluation of different scenarios for vacant plots occupation, automatically calculating the ratio between residential and non-residential places, in order to promote a more balanced Mixed-use index and a higher diversity for the neighborhood; and finally, a dynamic assessment of Spacematrix indicators before and after interventions, with the aim of identifying density limitations or potentialities within TOD scope. Figure 1 shows the approach workflow.

**THE CASE STUDY**

The case study comprises the application of the proposed approach on the existing district of Cascatinha, in the city of Juiz de Fora, Brazil (see Figure 2). The main goal of this study is to evaluate the proposed methodology potential to frame an area within the scope of TOD. Despite of being a predominantly residential neighborhood, the chosen district has a great potential to be a more autonomous and sustainable neighborhood, presenting some features that make it an ideal sample for evaluation of the proposed methodology, such as: a suitable...
Figure 2
Images from the 3D model of the neighborhood.
extension for TOD implementation (approx. 1 km diameter); relatively low density; no transport station; topographical complexity; available areas for new buildings; vicinity to important amenities such as a park, a hospital, a university, and a shopping center, among others; closeness to the city center, and; a good placement in the urban network, linking directly the city center to important city regions. This is a key scenario for assessing our approach towards more efficient TOD oriented planning, because besides demonstrating typical issues of the sprawling city paradigm, a situation found in several cities around the world, it also presents some important features for evaluating the methodology implementation.

The aforementioned approach steps were performed, considering the data of Cascatinha district. In that sense, the following information was obtained and transferred to the analysis model: the footprints, number of levels, uses (residential and non-residential) and topographical positioning of each building inside the district, in order to measure distances, slopes, possible connecting paths, diversity and density indicators; the location of each one of the amenities on the neighborhood, according to the aforementioned categories considered by Walk Index Calculator, in order to measure proximity, diversity and variety of locations; the identification of available areas for new buildings (vacant lots and non-consolidated places), seeking to provide room for new constructions and to modify the diversity of the district; the topographical network of neighborhood’s streets, with the view to consider slopes and distances for measuring SPC and WIC operations; and the design of blocks and lots, in order to provide density (Spacematrix) assessment. Thenceforth, the task was to apply optimization and simulation operations, aiming to increase transit accessibility, walkability and diversity related indexes, by the following actions, respectively: (a) look for the best location for insertion of a station, as long as the district does not have one; (b) insert only one amenity from each category, seeking to increase Walk indexes with the lowest number of new services possible; (c) evaluate different occupation strategies for vacant lots, considering Mixed-use index and Spacematrix indicators to help analyzing impacts from new buildings propositions.

RESULTS
The implementation of our approach provided some changes to the arrangement for the neighborhood, suggesting a better performance from the scope of TOD principles. In summary, the new settings provided: (i) an excellent Transit Accessibility, since the optimized insertion of a transport station permitted a high average Station Proximity score (see Table 3 and Figure 3); (ii) a greater walkability, as long as the optimized addition of new amenities provided an increase of the neighborhoods proximity, diversity and variety, in all analyzed categories, as shown in Table 3 and Figures 4, 5, 6; (iii) a neighborhood with more diversity, since the proposition of new buildings and their functions provided a more balanced Mixed-use index, seeking a greater equilibrium between residential and non-residential places - see Table 3; (iv) a more suitable density for a Transit Oriented Neighborhood, since parametrically controlled urban geometries made possible to regulate density, in a manner that supports more people (working or living) closer to transport hubs, as shown in Table 3.

Proximity and diversity indexes (both global and partial) increased after optimization tasks, suggesting that amenities became more closer and more balanced within the new district’s arrangement, as Figures 4, 5 and 6 shows.
DISCUSSION AND CONCLUSIONS

The approach proved to be helpful in order to provide dynamic assessment and optimization of principles derived from TOD. The positioning of the station was supported by optimization tasks that allowed to identify, among hundreds of options, the solution that provides the lowest average distance between the station and all other lots. In this sense, the obtained station proximity index was as high as it could get, considering the district’s configuration and the limitation of one station for it. Besides, the locations with worse Station Proximity scores were easily identifiable, and in this sense, this is a good starting point for further actions for transit accessibility improvement (the adoption of secondary modals for connecting these locations and the station, for example).

Multi-objective optimization addressed simultaneously multiple conflicting criteria for walk index answers, crossing data and performing calculations that would be more difficult to perform by traditional means. While proximity indexes considered...
only the nearest amenities, diversity indexes considered all surrounding amenities, seeking a greater balance (see Figure 7). This trade-off context was a key for providing greater proximity, diversity and variety indexes, meaning that services are nearer and in larger quantities along the district, which suggests more walkability. These three components of WIC can play an important role in TOD planning tasks, as long as they identify which services are more or less available for a particular plot, street, block or even the entire district. On the other hand, it also allows one to see which areas of the district are better or worse supported in relation to different categories.

Multi-objective optimization provides a set of solutions that are intended to be considered equally good (pareto-optimal solutions). It is an important possibility for urban planning processes, as long as it strengthens the planners' role in considering "non-programmable" aspects, for stipulating subjective criteria and priorities for decision making. Despite of not being directly optimized, density indicators play an important role in this approach, as long as they enable the visualization and evaluation of different scenarios for vacant areas occupation, guiding interventions and giving hints from building potential and mix of uses distribution. The Mixed-use index and Spacematrix indicators proved to be useful in the algorithmic implementation of this approach, given that they consider objective features for measuring diversity and density, respectively.

**Limitations, further developments and final remarks**

Despite the usefulness of a computational tool for supporting TOD oriented urban planning processes through evaluation and optimization of specific urban features, we identify some limitations in the presented approach. First, we recognize that Walk Index does not fully incorporate the diverse features that can influence the walkability of an urban area. Therefore, other variables that measure connectivity, density of streets network, and pedestrian friend-
liness features should be tested. Second, it would be important to identify which streets or stretches have higher recurrence in the walking paths, in order to identify the main pedestrian axes, which would be the high-priority places to promote an increase of pedestrian friendliness and mixed-use diversity. Third, as shown in our research, density has a fundamental role within the scope of TOD. In this context, variables related to populational density and the implementation of modals in a neighborhood should also be tested. Finally, considering the influence that inclivity has in Walk Index calculations, it is important to incorporate more specific guidelines in order to give support to penalty factors calculation.

This article seeks to facilitate the management of solutions in TOD planning processes, in order to delineate a starting point for computational approaches towards more efficient TOD proposals. Therefore, this study demonstrates the approach’s potential towards a more efficient TOD implementation methodology.

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