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Spatial suitability for urban sustainable densification in a borderland city

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The traditional approach to pursuit of sustainable urban development involves an integrated, long-term planning process based on a series of environmental, economic, equity and livability societal values, for creating healthy and prosperous communities that not only meet the physical needs but also the aspirations of their residents. Urban land plays a central role as the material basis of this process; therefore, assessing its suitability for livable and sustainable conditions is critical in contemporary cities. The efficiency of different urban density and centralization patterns, making livable communities demands to avoid oppressively dense or overly scattered and fragmentary development was discussed. In this research, land suitability for urban densification in the border city of Ciudad Juárez, Chihuahua, based on a spatial multi criteria analysis (SMCA) of environment, economy, equity and livability variables were assessed. The result model for each group variables showed that suitable areas for densification are associated with the consolidated part of the city. The main variables affecting suitability distribution in an integrated model were distance of public transportation routes, location of poverty zones and land values. Selecting potential areas for densification derived from this analysis requires appropriate strategies for affordable, diverse and accessible housing provision, which contributes to the creation of livable sustainable communities.

Key words: Urban densification, spatial multi criteria analysis, land suitability.

INTRODUCTION

Solving the current social, economic and environmental issues that threaten urban viability in many growing cities is one of the most pressing challenges for the decades to come in developing countries. It is predicted that by 2030, for every one person now living in cities in developed countries, there will be four in the cities of developing world, indicating that 90% of the growth in urbanization will occur in these regions (Burgess and Jenks, 2000).

Contemporary urban planning has shown a host of alternatives to attain the visionary idea of sustainable urban communities that gives their inhabitants opportunities for better lives (Godschalk, 2004; McKendry and Janos, 2015). This is in fact, the permanent quest in planning, finding a way to create places that are both sustainable and livable at the same time (Berke et al., 2006).

The traditional approach in pursuing sustainable communities involves an integrated, long-term planning

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process that seeks to protect the environment, expand economic opportunities, while meeting social needs for healthy and prosperous development (American Library Association, 2006).

Integration of these societal values, referred to as the three E´s (environment, economy and equity) triangle in the planning process, has been lately complemented by the incorporation of livability as a fourth node in what have been called the sustainability prism model 3E´s+L (Berke et al., 2006), for creating communities that not only meet the physical needs but also the aspirations of their residents.

From each perspective in this model, urban land plays a critical role as the material basis of certain processes in the city. The economic approach considers urban land as a commodity for the production, consumption and distribution of products and services for profit (Logan and Molotch, 2007).

From the vertex of the environmental values, the city is seen as an organic element that consumes resources and produces waste, making it particularly important for its functioning in the protection of its resources and interlinked ecosystems, dependent on land health and availability (Kennedy et al., 2011).

The equity perspective focuses on the need to solve conflict arising from the spatial distribution of resources and services, to create equal access opportunity structures, according to the needs, aspirations and relevance of the different groups in the community (Witten et al., 2003).

Incorporating the livability value into the urban planning process means considering the design of public spaces to encourage community engagement; an equilibrated mix of land uses and building types to accommodate a diversity of activities; the preservation of historic structures to promote sense of place; and the proximity to public mobility systems to enhance accessibility at the intra urban and regional scales (Bohl, 2002; Barnett, 2003). According to Berke et al. (2006), suitability factors for livable residential areas should include:

1. Accessibility and transportation systems
2. Safe environment free of danger of traffic and hazards
3. Privacy (secondary and tertiary streets)
4. Proximity to service, community facilities, shopping and activity centers, employment
5. Infrastructure capacity for basic services: water, sewer, gas, electricity and cable
6. Proximity and access to social facilities: educational system and health facilities
7. Proximity and everyday access to place-making in public space (streets, sidewalks and parks), open-space network, nature, places for recreation, relaxation and socializing
8. Mixed uses and diversity of activities
9. Preservation of historical structures: sense of place, belonging, pride and satisfaction
10. Housing compatible with different budgets and life-cycle stages (income and age).

Besides considering proximity to public space, service and social facilities, livable communities also requires a sufficient capacity of basic service infrastructure in an urban environment that guarantees safety, privacy and proper diverse housing conditions for people with differentiated needs and capacities at distinct age and productive life stages. All these requirements rely ultimately on the land as the foundation in which the materialization of urban structures occurs; therefore, identifying its potential and suitability is critical for livable and sustainable conditions in contemporary cities.

Land use planning for urban densification

Although, a general consensus has been achieved in the literature on close relationship between shape, size, density and land use pattern of a city and its sustainability, the relative efficiency of different urban density and centralization patterns for the rational use and distribution of its resources is still discussed. While certain urban forms and densities appear to be more sustainable, for example, in terms of mobility at the intra urban scale, others might have the same positive effects at the citywide or regional level (Burton et al., 2013).

What seems to be true in general is that, making livable communities demands shaping their growth to configure sensible and attractive patterns avoiding oppressively dense or overly scattered fragmentary development (Levy, 2016).

Achieving this equilibrium requires meeting a sort of physical and structural urban characteristics that guarantee accessibility and connectedness for easier interaction at the human scale. This condition, associated typically with relatively denser urbanization patterns, requires taking into account not only urban form, but also urban processes to achieve the elusive goal of a sustainable city (Neuman, 2005).

According to the vast amount of evidence, the common leapfrog low-density development pattern that dominated urban growth during the second half of the 20th century, resulted in the inefficient spread of fragmented suburban and exurban landscape (Burchell and Otros, 2002; Ewing et al., 2003), which proved to be an unsustainable model with very negative effects, exceeding the benefits of building residential areas on cheaper rural land, in close contact with nature (Irwin and Bockstael, 2004).

The large rural land consumption rates of urban sprawl placed intense pressure on environmentally sensitive areas (Johnson, 2001); increased the costs of public infrastructure and services (Carruthers and Ulfarsson, 2003; Zhao, 2010); augmented environmental pollution and traffic congestion (Allen and Lu, 2003); and fostered auto dependence with its derived negative effects on public health, due to the increasing commuting times (Frumkin, 2002; Ewing et al., 2003).

As one of the responses to the urban sprawl problem, the compact city paradigm requested for the need for more efficiently used urban spaces that maximized land savings and optimized intra urban transport for improved accessibility. This model, exhibited its own disadvantages in terms of the relatively low tradeoffs for energy resource savings; the potential for expanding transit use and promoting transit-oriented developments (TODs); the costs and benefits of suburbanization; the low efficiency gains from compactness; the impact of telecommunications on the density of development; and the poor acceptability of its higher residential densities (Gordon and Richardson, 1997; Burton et al., 2004).

Burgess and Jenks (2000) tentative definition of contemporary compact city calls for increase in built area and residential population densities to intensify urban economic, social and cultural activities through the manipulation of urban size, form and structure, in pursuit of the environmental and social benefits derived from the concentration of urban functions.

Nonetheless, there is need to clarify the actual effects of the compact city approach on ‘sustainable urban development’, since the particular relationship between spatial centralization and decentralization forces determining form and density in developing country cities, is complex and still barely understood (Burgess, 2002).

Besides the unsolved dilemma between the effects of urban sprawl and compactness, other pernicious trends threatening sustainability, such as the increase in mass production of poor quality housing and reduction of urban green spaces have produced inequitable environments affecting everyday lifestyles and accentuating growing inequity among cities at global level (Burton et al., 2013).

Planning, for the suitable combination of urban pattern, size and density produce the right equity and livability effects according to the economic potential, environmental capacity, social aspirations and cultural background of a community, a crucial undertaking of sustainability which is a goal to attain.

Since urban land use are complex systems integrated by components, factors and agents from both natural systems related to land resources and human systems related to land uses, the search for the ultimate sustainable urban form should take into account an integrated approach considering a wide array of key variables and their interrelations that truthfully represent the urban reality (Allen and Lu, 2003).

When it comes to land use planning and density, those interested in reducing the negative effects of suburban sprawl and automobile dependence have embraced the concept of “smart growth” in the last decades. The movement for smart growth aims to shape the future urban growth mainly from the logic of the “rural-to-urban transect”, having as one of the main goals, achieving neighborhood livability (Duany et al., 2010).

This approach prioritize the idea of planning the progressive increase of density from the more rural environments towards the urban core, and presents a more operational update of well-known ecological and traditional urban theories, such as the “valley section" of Geddes (1916) and the “rings of density” of Alexander et al. (1977).

The central idea is that density of dwellings should not be planned in a homogeneous way for the whole city, but in transects, to allow a harmonious integration of the city and the natural environment. This means that both high and low densities are desirable, with lower densities towards the edges of the city and higher towards the urban core.

In that logic, the Smart Code version 9.2 (Duany Plater-Zyberk and Company (DPZ) (n.d).), suggests the normative details for six sub-transects on the rural-to-urban transect:

T1: Natural Zone, T2: Rural Zone, T3: Sub-urban Zone, T4: General Urban Zone, T5: Urban Center Zone, T6: Urban Core Zone.

In this progression, the densest transect T5 and T6 corresponds to the more dense perimeter towards the center of the city: T6 consists of a high density and high height urban core with residential density up to 96 units/ac (gross (240 dwellings/hectare) mostly apartments); and T5 consists of high density and low height (3-to-5-story buildings) mixed use developments, with residential density up to 24 units/ac (gross (60 dwellings/hectare) and diversity of housing choices).

According to smart growth, density is beneficial for neighborhood livability and vice versa, provided that the capacity of each transect is respected. Higher residential densities favor mixed uses, which in turn improve neighborhood livability, and makes density acceptable:

“The “D word” is a contentious issue among planners and citizens. (…) higher-density developments do mitigate sprawl in several ways. Because they place more people on less land, they help to preserve open space. And since density support transit, they reduce dependence on the automobile. (…) Only if urbanism is practical, walkable and convivial, density will be tolerated by buyers, neighbors and elected officials” (Duany et al., 2010).

Although, it is not clear in the Smart Growth Manual, how to proceed methodologically to assess the suitable land in order to define the denser perimeters in a particular city, it can be concluded that it would be a good decision to identify the urban areas that fulfill the conditions to promote neighborhood livability.

In this research, the authors assessed the land potential for urban densification in the northern Mexican city of

Ciudad Juárez (CJ). This metropolitan area of approximately 1,391,000 inhabitants, located in the border with United States, experienced an accelerated expansion process along the last three decades of the XX century, due to the population attracted by the employment in the assembling industry and the possibility of immigration to U.S.

As part of the government´s response to the population growth, an intensive housing policy implemented at national level, fostered the mass building of low quality social housing in cheaper outskirt land, expanding further the urban grow of CJ (Flores et al., 2016). Thus, the kind of densification project considered in this proposal is well suited for medium income population sectors, to ease accessibility and to avoid social segregation.

Since the 1960s, the city has experienced a progressive growth of the municipal urbanized area, at higher rates than population growth, which has led to a progressive decrease of the gross density. According to IMIP (2010), in 1950, the city had 122,556 inhabitants and an urbanized area of 909.2 hectares, and a gross density of 153.21 inhabitants per hectare.

In 1980, the population amounted to 544,496 inhabitants and the urbanized area increased to 10,795.11 hectares, resulting in a decrease in gross density to 60.3 inhabitants per hectare. In 2008, the city had 1,371,494 inhabitants in an urbanized area of 30,052.9 hectares, which expresses again a decrease of gross density to 42 inhabitants per hectare. Hence, there is an urgent need for adequate strategies to promote re-densification, according to the suitability conditions of this borderland city.

MATERIALS AND METHODS

The study was based on a land suitability analysis (LSA), which provides a rational decision support frame to determine the suitability of a specific area, regarding its intrinsic characteristics (Chen, 2014).

Based on spatial multi criteria analysis (SMCA) performed through a geographic information system (GIS) process, land suitability assesses the aptness of a given location to support a considered use (Carr and Zwick, 2007). The specific importance given to the criteria in the SMCA was determined through a spatial analytic hierarchy process (AHP) relying on expert opinions on the perceived effects of different factors on site suitability, in this case for urban densification (Jafari and Zaredar, 2010).

Taking into account, the equity, economy, environment + livability (3Es+L prism), a spatial model was integrated using 46 variables distributed in each of the four categories. For every variable, the parameters and criteria that a specific location should meet and considered suitable for densification was defined. All the variables, integrated into a digital spatial database covering the urban area of CJ were derived from official databases, field data, and remotely sensed imagery. Variables were then converted into raster format using the WGS84 UTM 13N spatial reference system at a 30 m spatial resolution. The parameters specified the original units used to code each variable, while the criteria define the direction in which each variable was reclassified to meet a suitable condition.

The group of environmental values was composed mainly by physical variables that determined the potential for densification based on the land capacity to harbor higher population densities. First, only locations with altitude below 1300 m.a.s.l. and terrain inclination lower than 10° were considered, to set a restriction for urban development on the mountain area. Then, the advantage of densification in areas relatively close (<DIST) to different type of water bodies were considered, due to the benefits of surface temperature regulation and aesthetic value, while avoiding immediate contact with restriction buffers of different sizes for safety and protection (VOID).

In the other direction, the authors sought to keep denser areas away (>DIST) from potential risks such as flooding plains, pluvial drains, gas and power lines, and high risk intermittent streams, with restriction buffers according to applicable normative regulations and official recommendations (Comisión Reguladora de Energía, 2001; SEDESOL, 2011; CFE, 2014).

Other potential risk natural and human-dependent features such as freight routes, erosion prone areas and geologic faults were also considered deterrent factors, so, the farther away from them, the more suitable the location for densification (>LOC). Urban contention zones proposed by SEDATU-CONAVI (2015) were also considered. The more consolidated the polygon, the more suitable the densification (Table 1).

The economic variables included the location of retail commerce units and commercial malls, from the National Statistical Directory of Economic Units (DENUE) (INEGI, 2016); as wells as availability of employment in commercial activities at the Geostatistical Basic Unit (AGEB) level from the National Census of Population and Housing (INEGI, 2010).

Accessibility to retail commerce was considered an important part of the advantages for any location with higher population density, due to the necessity to satisfy a wide variety of supply demands, so the closer a given location (<DIST) to the concentration of commercial activities, the more suitable the densification (>LOC) (Table 2).

Given the fact that CJ has a well-established industrial vocation with 61.9% of the employment concentrated in the manufacturing sector (INEGI, 2015), location of industrial parks and higher availability of employment in the manufacturing industry were also considered as important factors due to the intra mobility requirements of a big population share. Thus, the proximity of these features was considered a favoring factor for suitability, except for a buffer of 100 m around industrial parks (VOID), to avoid direct contact with denser residential areas.

The location of functional urban centers was also included, since closeness to these service and employment areas is an indicator of higher concentration of urban activity. Finally, in this group of variables, land value at the AGEB level was included, given that the potential for densification projects of medium income housing is highly influenced by the cost of land, favoring (FAV) therefore areas within a price range of $250 to 1000/m^2.

In the third set of the equity values, a group of variables associated with the presence and accessibility to infrastructure and urban facilities that improved equity conditions in the community was included. First, the advantage of locations closer to educational facilities (<DIST), favoring different accessibility ratio buffers depending on the school level, was considered.

Nearness to health, cultural, recreation and service facilities were also considered advantageous in the model. Since house abandonment and land underutilization have been identified as critical threats of urban development in Ciudad Juárez, availability of brown fields and areas with higher percentage of uninhabited housing were also considered desirable candidates for densification.

Nonetheless, the model proposed avoiding increased density, the so called poverty zones (IMIP, 2009), since these do not have proper capacity to support higher concentration and require a different strategy for development. Closer location of domestic natural gas distribution lines was favored, as well as longer

Table 1. Environmental variables.

Variable	Parameter	Criterion
Altitude	masl	VOID >1300
Slope	Inclination in degrees	<SLOPE>LOC $_{\text{VOID}>10^\circ}$
River	Distance in meters	<DIST> LOC $_{\text{VOID}<80}$
Main Irrigation ditch	Distance in meters	<DIST>LOC $^{\text{VOID}<16}$
Secondary Irrigation ditch	Distance in meters	<DIST>LOC $^{\text{VOID}<12}$
Waterbody	Distance in meters	<DIST>LOC $^{\text{VOID}<20}$
Flooding area	Distance in meters	>DIST> LOC
Pluvial drain	Distance in meters	>DIST>LOC $^{\text{VOID}<20}$
Main gas line	Distance in meters	>DIST>LOC $^{\text{VOID}<50}$
Power lines	Distance in meters	>DIST>LOC $_{\text{VOID}<42}$
High risk stream	Distance in meters	>DIST>LOC $_{\text{VOID}<20}$
Freight route	Distance in meters	>DIST> LOC
Erosion prone area	Distance in meters	>DIST> LOC
Geologic fault	Distance in meters	>DIST> LOC
Urban contention zones	SEDATU zones	<U>LOC $_{\text{LOW}=0}$

Table 2. Economic variables.

Variable	Parameter	Criterion
Retail commerce	Distance in meters	<DIST>LOC
Commercial mall	Distance in meters	<DIST>LOC
Commercial employment	Number of job vacancies	>VAC>LOC
Industrial parks	Distance in meters	<DIST> LOC $_{\text{VOID}<100}$
Manufacturing employment	Number of job vacancies	>VAC>LOC
Functional center	Distance in meters	<DIST>LOC
Land value	Cost in \$MX/m^2	<COST>LOC $_{\text{FAV250-1000}}$

distances of main sewer lines, with a voiding buffer of 20 m, given the risk of line collapse repeated in Ciudad Juárez during the raining season in the last years throughout the city (Table 3).

The four vertex of our urban sustainability model was comprised mostly of variables associated with accessibility conditions. The authors sought locations close to primary and secondary streets, public transportation routes, stops and intersections to ease the access at the intra urban level by different mobility systems.

In the case of the public transportation variables, a buffer of 1 sq km representing a radius of the walkable distance for convenient connection between service and residential areas and transportation was favored. As complement, more suitable locations near bikeways projects, parks and green areas were considered to improve the livable conditions and public space access in denser populated areas. Access to services and urban facilities was also considered in binary variables to favor neighborhood centers and mix compatible land uses, with population densities between 50 to 10 inhabitants per hectare Table 4.

According to the proposed criteria, all variables in raster format were reclassified using an ordinal scale from 1 to 5 with higher values, indicating more suitable locations. The importance of each individual reclassified variable was evaluated by a group of experts in a pairwise comparison, establishing a ranking within each category. Agreement in rank assignment was evaluated in several rounds until variability for each factor was less than one standard deviation. The average rank was then used to calculate a weighted ranking for each variable according to the following function (Malczewski, 2004):

$$w_j = (1 / r_j) / \sum (1/ r_j) \qquad (1)$$

where w_j is the weighted inverse ranking, r_j is the group agreed ranking and $1/r_j$ is the reciprocal group agreed ranking. Each variable was then multiplied by its corresponding weight and combined into integrated models for each of the four categories with a weighted overlay sum function (Samad and Morshed, 2016). Category models were then combined in a general model with 30% of weight assigned to each of the equity and livability models, and 20% to the environment and economic components. From the final model, the areas above 2 standard deviations were selected to identify only the areas with the most suitable conditions for densification in the study area. These zones were finally overlaid on a spatial database of the available vacant lots to identify potential sites for residential densification as input for the next phase in the project.

RESULTS AND DISCUSSION

On the basis of the model for urban sustainability

Table 3. Equity variables.

Variable	Parameter	Criterion
Preschool	Distance in meters	<DIST>LOC $_{FAV<750}$
Elementary school	Distance in meters	<DIST>LOC $_{FAV<500}$
Middle school	Distance in meters	<DIST>LOC $_{FAV<1000}$
High school	Distance in meters	<DIST>LOC $_{FAV<5000}$
Hospitals	Distance in meters	<DIST>LOC
Cultural center	Distance in meters	<DIST>LOC
Recreation facility	Distance in meters	<DIST>LOC
Public servicie facility	Distance in meters	<DIST>LOC
Community center	Distance in meters	<DIST>LOC
Brown field	Availability	FAV Av, LOW NotAv
Uninhabited house	% uninhabited house/block	>%UH/B>LOC $_{FAV>40}$
Poverty zones	Distance in meters	>DIST>LOC $_{VOID <PZ}$
Gas lines	Distance in meters	<DIST>LOC
Main sewer lines	Distance in meters	>DIST>LOC $_{VOID<20}$

Table 4. Livability variables.

Variable	Parameter	Criterion
Primary street	Distance in meters	<DIST>LOC $_{VOID <100}$
Secondary street	Distance in meters	<DIST> LOC
Public transportation route	Distance in meters	<DIST>LOC $_{FAV<564}$
Transportation route intersection	Distance in meters	<DIST>LOC $_{FAV<564}$
Semimasive transportation route stops	Distance in meters	<DIST>LOC $_{FAV<564}$
Parks and green area	Distance in meters	<DIST>LOC
Bikeway	Distance in meters	<DIST>LOC
Population density	People/ha	<DEN>LOC $_{FAV50-100}$
Neighborhood center	NC	FAV NC, LOW NotNC
Land use	Compatible uses	FAV Comp, LOW Incomp

proposed by Berke et al. (2006) four spatial sub models were created, one for each of the societal values categories; environment, economy, equity and livability. These models, with a continuous scale ranging from 1 to 5 indicate areas less or more suitability for densification, according the combined weighted effect of the variables considered.

Environment model

Suitability for densification derived from the environmental variables resulted in a model ranging from 1.6 to 4.4, with higher values towards the urban fringe in the rural portions of the study area.

In fact, the farther it is from the consolidated western part of the city, the higher the suitability values in the model (Figure 1a).

This model exhibits in addition, void zones in the mountain area and in buffers along drains, ditches, power and gas lines, and high-risk intermittent streams. The lower values, assigned to 41% of the pixels, were located where high slopes and erosion prone areas overlap flood plains and close to intermittent streams.

According to the AHP analysis, most of the weight in this model (55.1%) was assigned to environmental risk-related variables: 30% of the weight was placed on the flooding areas variable; 15.1% on the high-risk intermittent streams; and 10% on the erosion prone areas.

This valuation reflects the experts' concern on the effects caused by extreme meteorological events, recurrent in the Ciudad Juárez region during the summer season, which have already caused considerable material loss and threaten human lives, in social housing developments built in the last decade over flood plains of the southeastern portion of the study area. The rest of the weight was evenly distributed among the rest 15 variables, with irrigation ditches and geologic faults considered as the least important.

Economy model

As some of the main urban development drivers, the economic variables produced a model that concentrates suitability for densification, associated with the consolidated part of the city. This model ranged from 1.36 to 4.69 and gave more suitability value to the concentration of commerce and industrial activity, given the location advantage in terms of employment accessibility (Figure 1b).

Favorable access to job sites for middle-income families has always been considered a location asset that fosters productivity in agglomeration economies (Brinkman, 2016); therefore, this is a desirable condition for denser residential areas in Ciudad Juárez, where more than half of the population is labored in the manufacturing sector.

Another important factor, weighted in fact with 38.6% of importance in this model by the AHP analysis, was the land value. It is widely recognized that success of densification projects oriented to middle income population sectors are only viable if they are built on competitive price land that is accessible to lower income strata (CITE). High-priced land tends to increase the final cost of the residential projects limiting the economic viability of socially oriented densification projects.

The other two variables accounting for more than 32.2% of the weight in the model were retail commerce (19.3%) and commerce job density (12.9%), which once again gives an important value to the business activity related to commerce, because of the increasing demand of retailing supply in more populated areas. The remaining 30% of the weight was distributed in the other four variables.

Equity model

The variables integrating the equity model considered mainly the favorable effect of even accessibility to urban services and facilities, as a means to improve social conditions for sustainable urban communities. These variables include mainly the access to education services from preschool to high school level, to hospitals and to other urban services.

For this reason, higher suitability values were located in the consolidated part of the city, where most services of this type can be found. Nonetheless, suitable areas in this model are more sparsely distributed within the urban border given the effect of pre and elementary schools that are installed relatively early in the newly occupied areas of the urban fringe, and that were weighted with15.4 and 10.3%, respectively (Figure 1).

Through the AHP analysis, more weight was assigned to the distance to poverty zones (30.8%) given the importance of not promoting densification on areas with limited urban and socioeconomic capacities. The poverty polygons (IMIP, 2009) themselves were void in this model. Despite the fact that densification has been proposed traditionally in many urban policies, as the solution towards the reduction of poverty, its efficiency as a planning strategy in poor cities, still has many challenges (Caicedo, 2015; Fataar, 2016).

As a borderland city, Ciudad Juárez concentrates in its poverty zones which are highly vulnerable immigrant communities, so, a case for densification in these areas would have to consider not only the current precarious conditions in housing and urban infrastructure, but also the cultural and socioeconomic profiles of their inhabitants. The remaining 53.5% of the weight in this model was assigned more or less evenly among the other eleven variables.

Livability model

For the fourth node in the 3E’s model for urban sustainability, the livability model shows suitable areas for densification within the extension of the Ciudad Juárez urban area, highly associated with the road and transport infrastructure (Figure 1d).

This result makes evident the important role of public and alternative transportation means in favoring livable conditions for a TOD-like type of community. TOD seeks to create compact, pedestrian-oriented, livable and sustainable communities built around mass transit intersection and corridors, designed to encourage ridership on public transportation (Holmes and van Hemert, 2008).

Despite this being a desirable situation in Ciudad Juárez, it is important to recognize that this degree of human interaction in the public domain is difficult, if not impossible to achieve, in much more socially car-dependent urban contexts (Curtis et al., 2009). Public transportation routes thus, were assigned 30.4% of the weight in the model, with the highest value categories in all related variables belonging to walkable distances that ease approachability. Void buffers appear along all main roads, and farther areas towards the boundaries of the study area were less suitable due to constrained accessibility.

Other conditions for livability in TOD communities are also the high-density mixed-use buildings around a transit corridors or urban centers, which in this case are represented by neighborhood centers with 17.1% of the weight and compatible mix land use with 11.4%. This combination would potentially have the effect of encouraging cycling and walking, controlling the flow of automobile traffic and reducing the amount of land devoted to parking (Brendel and Molnar, 2010) or under-utilized as vacant space, as compared to conventional development pattern in Ciudad Juárez.

It is believed that compact development with integrated land uses that cluster commercial, public, and recreational services near transit stations and within walking distance of residential and employment areas, creates a pedestrian friendly environment that reduces the need of automobile use and shortens travel time and distances, reducing

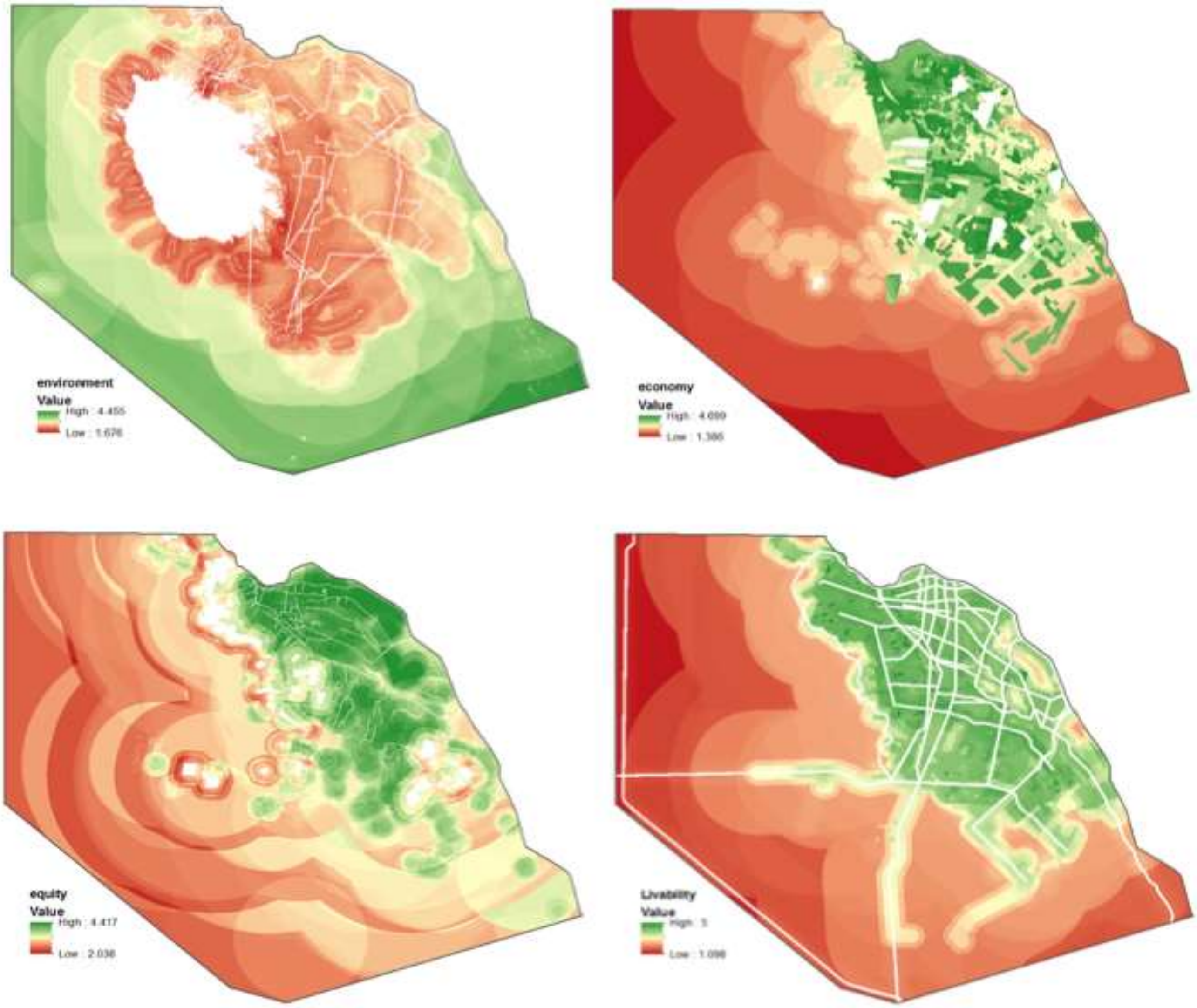

Figure 1. Environment (a), economy (b), equity (c), and livability (d) models.

overall traffic congestion, and improving daily livable conditions for people (Goodwill and Hendricks, 2002).

The final model integrated with the proposed sum weight distribution for each of the four categories shows most suitable areas in the Ciudad Juárez urban area with a mean value of 2.92 in a rather stretched range from 1.87 to 3.98 in the 1 to 5 suitability scale (Figure 2). In this case, only 23.23% of pixels showed values above the average and could be considered fairly suitable for densification.

After separating only the areas with positive suitability values 2-standard deviation above the mean, a total of 6297.44 hectares was finally obtained with potential for densification, which means 5.72% of the study area. Out of the 46 variables, 12 were assigned 60% of the weight in this final model, being the three most important: public transportation routes (10%), poverty zones (9.2%) and land value (7.7%).

Marginal suitability areas in the model, occupying 76.76% of the study polygon were located mostly in the rural area, to west of the mountain range marked as a large void area. Despite low land costs in these natural zones, lower suitability values here are due to the low accessibility to transportation systems, and urban service provision. Accordingly, medium suitability areas were located mainly along the urban fringe and over the southern portion. These areas are not very well connected by public transportation nor do they have the best access to urban services.

High suitability areas for densification in this model were distributed along residential and commercial areas in the city. Three main clusters are visible, one in the northwestern close to the international border; one around the consolidated historic center; and one more in the

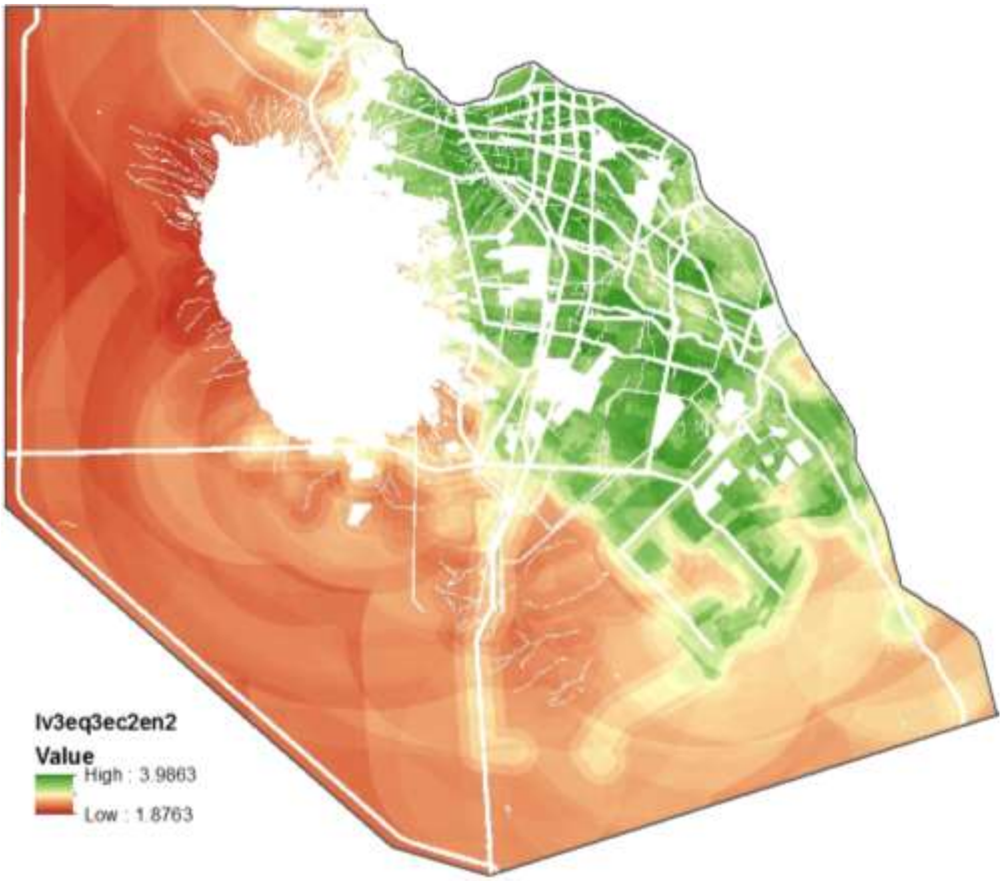

Figure 2. Final integrated model (Environment 20%, Economy 20%, Equity 30% and Livability 30%).

southwestern where the city extended its boundaries in the 1990 decade. These suitability patterns might allow different alternatives to designing specific densification projects, since in the first case, there is a fairly consolidated area dominated by medium to high-income residential and industrial use. In the second case, the suitable areas were located over a deteriorating portion of city characterized by high abandonment residential rates around the downtown. Finally, the third zone with high suitable values is occupied by large social housing developments alternative of industrial parks.

These results are the input for the next phase of the project, where specific vacant lots will be identified in the suitable zones to develop specific residential projects for densification. Each of these potential areas will require a different kind of solution, given their particular socioeconomic and urban profiles. These solutions should consider among other precepts, designing an adequate strategy to subsidize affordable housing, principally in places where proximity to transit provides ready access to jobs and services without the added financial burden of automobile ownership.

This kind of housing should be alternated with a diversity of housing options for a healthier social environment, that allow at the same time, access to multiple market segments, thereby achieving faster product absorption (Duany et al., 2010). Taking into account these principles will increase the chances of successful urban interventions for more equilibrated livable communities at the neighborhood level in this vibrant industrial borderland region.

Conclusion

Modeling suitability for densification on a borderland city such as Ciudad Juarez and applying a spatial multi criteria approach has proved to be an effective method to combine a wide array of factors affecting urban and socioeconomic potential to incorporate projects that promote denser livable communities.

After running the model, it can be concluded that the compact city paradigm is possible, but not in the city as a whole or homogeneously, and thus it is of a crucial importance to evaluate which part of the city is suitable for densification and which is not. Especially in the case of cities characterized by rapid and disorderly growth, defining denser perimeters is not as simple as ideal concentric rings. In this context, the complexity of assessing suitability for a dense growth that is also livable and sustainable depends on many factors and only the computerized methods of multi criteria analysis can be integrated. The 3Es+L prism model (Berke et al., 2016) proves to be an appropriate approach given that the success of high density developments depends to a greater extent, on the neighborhood livability. This question can be asked:

1. Is it important to consider equity and habitability?
2. How the model would have turned out, if one of the variables (environment, economy, equity and livability) had not been considered?

The model assesses the land capacity to support high population densities, considering it as desirable conditions:

1. Environment: Avoiding the exposure to natural and human-dependent risks.
2) Economy: Proximity to higher concentration of urban activity, employment and medium land value.
3. Equity: Even accessibility to urban services and public facilities; and
4. Livability: Pedestrian-oriented and livable communities with diverse mobility and accessibility.

So, if any of the four variables had not been considered, it would mean exposure of higher density residential developments to environmental risk and natural disaster, or the lack of economical and sociocultural opportunities, and urban vitality and amenities. Assigning 30% of weight to equity and livability prevents exclusion, segregation and socio-spatial fragmentation, which are very critical problems in cities in developing countries.

How can we describe the suitable areas for densification? These areas on one hand, have proximity and accessibility to: public transportation routes, primary and secondary streets, stops and intersections, different mobility systems, mixed uses areas, walkable distances to parks, green and open public spaces; also closeness to higher concentration of urban activity, services, commerce, to higher job density areas, medium land value areas, infrastructure, health, cultural, recreation and service facilities, to domestic natural gas distribution lines.

On the other hand, they are safe areas and protected from risks, since they avoid and keep away: geologic faults, slopes and erosion prone areas, intermittent streams, higher land value areas, restriction buffers for safety and protection of water bodies, flooding plains, pluvial drains, main gas, sewer and power lines, freight routes, main roads and poverty zones.

Thus, it is fair to say that these suitable areas are seen as an opportunity to promote "smart growth" in Ciudad Juárez since the "smart growth communities consist primarily of neighborhoods, each of which satisfies the ordinary daily needs of its residents within walking distances. Each neighborhood should contain a balanced mix of uses, including large and small dwellings, retail spaces, workplace and civic buildings. The most complete neighborhoods also provide their residents with pedestrian access to schools, day care, recreational centers, and a variety of open spaces, as well as opportunities for food production (Duany et al., 2010).

Non-suitable areas for densification in Ciudad Juárez, according to the results of the model, in the case of Ciudad Juárez, should not promote a dense development in the more rural areas to the south and west of the mountain range (marked as a white large void area), where the model identified the most marginal suitable areas.

The west of the mountain range only showed medium results in the variable environment, while low suitability was identified in terms of economy, equity and livability. Towards the edges of the city to the south of the mountain range, only the variable, economy presented suitability, reaching lower suitability in terms of environment, equity and livability. This means that despite the low land costs, these areas do not fulfill the conditions to be considered suitable for medium or high densities and intense residential use, since low density is needed, allowing a harmonious integration to the natural environment. Nevertheless, this does not mean that they cannot be developed, but that developments should target populations who are not affected by automobile dependency and lack access to jobs, services and public facilities.

Although, successful pedestrian-oriented, compact and livable communities are not only dependent on land-use decision, an evaluation of the best suited locations to fulfill these desirable conditions is a first step to achieve balanced and smart growth.

These suitable areas for densification represent a great opportunity to create livable, sustainable, safety and self-sufficient communities, to reduce sprawl, as well as the demand for mobility and spending on infrastructure and public facilities, also, to create inclusive communities properly to integrate the provision of affordable housing for medium income population sectors in Ciudad Juárez. For this reason, it is crucial to regulate land costs in these areas, as this continues to be the main obstacle to planning the provision of social housing with equal rights to the city.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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