

# GIS-based Modelling and Estimation of Land Use Mix in Urban Environment

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*Abstract:* - Mixed-use development is widely discussed subject of urban sustainability. It helps to cope with energy and transportation related problems in urban environment, forms the compact, walking-friendly, economically and socially vital communities by fusing together different functions such as residential, commercial, and recreational land uses. Although mixed land use is the key planning principle of compact development and this term frequently appears in the urban planning strategies and literature, it is rarely elaborated upon with substantive and empirical support. Furthermore - the standard mathematical models and methods for quantifying this parameter in most cases miss the human scale and therefore give inaccurate results. This study performs functional mix analysis of Klaipėda City (Lithuania) with emphasis on urban travel distances. The demonstrated model proves the importance of scale factor and adds another dimension to existing methods.

*Key-Words:* - Urban Metrics, Urban Sustainability, Mixed Use Development, Urban Compactness, City Planning, Location Theory, Spatial Metrics, Spatial Structure, City Clusters.

## 1 Introduction

More than half of world's population lived in cities in the year 2008, and the urbanization is process is becoming progressively faster with every year. If current trends in urban expansion continue, urban energy use will increase more than threefold, from 240 EJ in 2005 to 730 EJ in 2050 [1]. The study model for 254 world cities has shown that urban planning and transport policies can limit the future increase in urban energy use to 540 EJ in 2050 and contribute to mitigating climate change [2].

The ineffectiveness of urban sprawl, excessive land consumption in the past decades has led the governments to formulate political strategies focused on the pattern of urbanization.

It is proved that urban system efficiency is liked with the dispersion of urban functions. The resource and energy use increases drastically if urban functions are dispersed and disconnected [3, 4]. Within the research community there is a wide agreement that compact developments with a high mix of land use functions are preferable over low density or mono-functional development [5]. Mixed use planning in urban environment helps to use energy for infrastructure and transportation more efficiently, forms the compact, walking-friendly, economically and socially vibrant communities by fusing together different functions such as

residential, commercial, and recreational land uses [6, 7]. The key point is the possibility in the mixed use environment to find all the objects of daily needs in close neighborhood and therefore be able to reduce private car use, travel distances, travel time and save the resources associated with these activities [2].

The concept of mixed-use development is proposed against the functional division in urban design and planning in Western cities in the 20th century. Influenced by the principles of functionalism, zoning had been firmly entrenched since the 1920s in the European and North American cities as a strategy to increase efficiency and safety by separating incompatible land uses. Zoning had played an important role in the reconstruction and recovery efforts after World War I. However, like many other well-intended urban policies and planning initiatives, functional zoning created many of its own problems as it was repeated mechanically in these cities, such as congestion, pollution, urban sprawl, workplace-residence separation and the loss of urban vitality [8].

Support for mixed-use development has increased in the literature and by interdisciplinary researchers around the world [9, 10]. For developed countries such as the United States, Canada, Japan and European countries, in which the urbanization

level is high, mixed-use development has become a key element in both modern urban theories and planning practice [11]. The functional configuration and dislocation of land uses within the city environments has become widely discussed topic of concern [7].

## 2 Problem Formulation

Despite growing research interest in the impacts of urban land use mix, there have been few methodological analyses of how best to measure urban mixed use environments. Some methods for the estimation of land use mix level exist and are used by social geographers, social economists and statisticians [12].

The concept of urban land use mix implies that nearby land uses or activities have an influence over each other across a limited spatial range. Therefore urban mixed use measures all contain two concepts: distance and quantity and reflect how the quantity and proximity of one type of land use influences another.

Most of the recent research studies in this subject come from geographical and social science background. These studies deal with the sum of each land use, most commonly the percentage of each urban land cover type and are usually based on crude estimations [13-16]. The number of objects and complexity of calculations mostly depend on GIS data available, which in recent literature is usually limited to land covers produced from satellite images. More precise data is also available from the same sources and additional "Street View" images but it requires more knowledge and is more time-consuming in data-preparing and computation stages (see case study presented).

### 2.1 Integral Estimation Measures

The integral estimation measures used to define level of land use mix come from statistical analysis field. These measures do not take into account the spatial locations of urban objects directly. The statistical methods proposed by different recent researchers very often don't take into account the actual urban interactions and Most of these estimations are based on simple percentages, the Balance Index, the Entropy Index and the Herfindahl-Hirschman Index. The equation for the *Balance Index* is the most simple measurement and only enquires the total, areal level amounts of land use for two categories:

$$BAL = 1 - \frac{|X - aY|}{(X + aY)} \quad (1)$$

The variable  $a$  is an adjustment factor that reflects the relative balance of land uses  $X$  and  $Y$ . If there are expectations of approximately the same level of  $X$  and  $Y$  (i.e. workers and jobs), an adjustment factor may not be necessary.

The *Entropy Index* is a measure of land use mix which takes into account the relative percentage of two or more land use types within an area. Higher levels of Entropy mean higher mix level. The Entropy Index varies from 0 to 1. Let  $P_j$  be the percentage of each land use type  $j$  in the area, and let  $k \geq 2$  be the number of land use types  $j$ .

$$ENT = - \left[ \sum_{j=1}^k P^j \ln(P^j) \right] / \ln(k) \quad (2)$$

The Entropy measure is symmetric with respect to land use types. That is, suppose the distribution of three land use types is 50%/35%/15%, this will produce the same Entropy Index as a distribution that is 15%/50%/35%. It means that the real urban interaction between different uses is not taken into account.

The *Herfindahl-Hirschman Index* (HHI), a commonly accepted measure of market concentration in economics, can also be used to assess the level of land use mixture. If there is only one land use type present in an area, HHI will equal 1, and if all land use types are equally present, then  $HHI = 1/k$ . Therefore, the higher values of HHI correspond with less land use mix. Let  $P_j$  be the percentage of each land use type  $j$  in an area, and let  $k \geq 2$  be the number of land use types  $j$ .

$$HHI = \sum_{j=1}^k (100 * P^j)^2 \quad (3)$$

HHI is also symmetric with respect to land uses and especially sensitive to the size of the most prevalent land use.

### 2.2 Measures for Estimating Evenness of Spatial Distribution

The methods that are sensitive to spatial distribution include the Clustering Index, the Dissimilarity Index, the Exposure Index, and the Gini Index. To calculate these Indexes researchers usually divide analyzed territory into districts or cells.

The *Clustering Index* summarizes the degree to which any single land use type is clustered in a relatively compact area, and is thereby segregated from other land uses. The *Clustering Index* ranges from 0 to 1 with higher values indicating lower levels of land use mixing, or higher levels of land use clustering.

Let  $Y$  be the total amount of non-residential land in an area and let  $s_i$  be the percentage of the area's non-residential land which is contained in district  $i$ . Let  $y_i$  and  $z_i$  be the amount of non-residential land and total land in district  $i$  respectively. Both  $i$  and  $i^*$  are indices for districts, and  $d_{ii^*}$  represents the physical distances between the centroids of pairs of districts:

$$CLST(Y) = \frac{\sum_{i=1}^n s_i \sum_{i^*=1}^n y_{i^*} e^{-d_{ii^*}} - \frac{Y}{n^2} \sum_{i=1}^n \sum_{i^*=1}^n e^{-d_{ii^*}}}{\sum_{i=1}^n s_i \sum_{i^*=1}^n z_{i^*} e^{-d_{ii^*}} - \frac{Y}{n^2} \sum_{i=1}^n \sum_{i^*=1}^n e^{-d_{ii^*}}} \quad (4)$$

The *Dissimilarity Index* measures the degree to which the distribution of different land uses within cells or districts is similar to the distribution that occurs in the area as a whole. The value of the index ranges between 0 and 1, and in this case a value of 0 corresponds to a higher level of land use mix. The variable  $a$  is an adjustment factor that reflects the relative balance of land uses  $X$  and  $Y$ .

The measure can be implemented for two or more land use types ( $k \geq 2$ ). For two land uses, where  $r_i$  is the percentage of an area's residential land use in district  $i$  and  $s_i$  is the percentage of the area's non-residential land use in district  $i$ , the formula is:

$$D = 0.5 \sum_{i=1}^n |r_i - s_i| \quad (5)$$

The formula for *Dissimilarity Index* to multiple land use types is as follows:

$$D(k) = \frac{1}{2} \sum_j \frac{1}{(Z - X^j)} \sum_i |Zr_i^j - z_i| \quad (6)$$

For the *Dissimilarity Index*, if the area as a whole is out of balance, the Dissimilarity Index will only indicate the degree to which districts vary from the pattern of a whole area.

The *Exposure Index* measures the degree of potential contact or possibility of interaction between two subject groups. The Exposure Index ranges between 0 and 1 with higher numbers indicating greater land use mix or equivalently, a higher opportunity for interaction.

$$EXP(x) = \sum_{i=1}^n s_i p_i \quad (7)$$

The *Gini Index* can also be adapted as a measure of the evenness of the distribution of two different land use types. It ranges from 0 to 1, where 0 means a greater mix of uses (or perfect equality of percentages) and 1 means maximum segregation of land uses. The Gini Index is more difficult to calculate than most of the other measures because all of the districts must be sorted in the correct order and cumulative sums must be calculated as a preliminary step.

Let  $r_i$  be the ratio of the residential land in district  $i$  to the residential land in the area overall, and let  $s_i$  be the ratio of the non-residential land in district  $i$  to the non-residential land in the area. Sort the districts in order of ascending slope in so that  $r_i/s_i < r_{i+1}/s_{i+1}$ . Then let  $\sigma r_i$  and  $\sigma s_i$  be cumulative percentages of  $r_i$  and  $s_i$ , respectively. The sorting ensures that for all  $i$ ,  $\sigma r_i < \sigma s_i$ , which in turn ensures that the Gini curve is below the slope 1 curve through the origin. Then the formula is:

$$GINI = \left| 1 - \sum_{i=1}^n (\sigma r_{i+1} + \sigma r_i)(\sigma s_{i+1} - \sigma s_i) \right| \quad (8)$$

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### 2.3 Computation of Results and Problems Associated With It

All the methods described above are just mathematical expressions given to calculate the possible interaction levels between the cells or districts. These methods are not sensitive to spatial locations of cells or districts; therefore we call it integral measures and measures for estimating evenness of spatial distribution. In addition to these methods the computation cycle must be launched, especially when we have to deal with huge amount of urban objects (cells).

The general idea when performing such calculations is to measure the distances between the objects or object centroids and add attraction coefficient according to the distance [17-21].

In most cases the index of interaction is divided by squared distance and it is completely wrong in urban environment where the distance matters a lot. The problem of defining the distance itself is also very prevalent in current research, most authors use

Euclidean distance, but in urban structure it does not give correct results because of town blocks, nature obstacles like rivers, transportation network. The ontology of urban network is discussed in recent research [22].

The methods for eliminating distance definition problems are being developed, but in this paper we focus on the idea of *human scale distances*. These are the average distances that people cover using different modes of transportation (by foot, by bicycle, by public transport or by private car). Only these distances, not the squared meters or kilometres really matter when considering the urban distances. Human scale distances in our research include 4 main types:

Journey made by foot – it is commonly agreed that the urban distances comfortably covered by foot are about 10 minute walking distance which is 500-700 meters. This distance is of the most importance when calculating the interaction of urban objects, because it lets to reach the destination objects by foot. The pairs of objects that are closer than this are interacting in most sustainable way. It is enough to analyse compactness and level of land-use mixing if we think about sustainable transportation or pedestrian-friendly urban environment.

Next important distance is journey made by bicycle which is usually longer and in most studies is agreed has the limit of 20 minutes – i.e. 5000-7000 meters. This distance between a pair of objects also means possibility for great interaction and what is important by the sustainable mode of transport.

The comfortable distances covered when traveling by public transport and private car are limited to around 45 minutes and equal to 35-40 km in urban environment. These distances are too large in most cases and are not important when focusing on land use mix and sustainable transportation.

### 3 Case Study

This study is performed on the GIS database of Klaipėda city, Lithuania. This is demonstrational study with the methods developed by Urban Planning Institute of Vilnius Gediminas Technical University. The methods were used in town planning when working on general plans of smaller Lithuanian towns and other urban projects. The results helped planners to find best locations, and best proposed functional uses for city blocks.

Klaipėda city covers 95 m2 and at has around 157 000 inhabitants, from which 78 000 are working people. The city has a sea port in Baltic sea and is at great degree industrial city. It is administratively divided into 12 districts and smaller divisions which

can be called neighbourhoods according to modern urban terminology (Fig. 2, Table 1).



Fig.1 The functional zoning map and districts of Klaipėda city

Table 1 The names of districts and neighbourhoods of Klaipėda city

District name	Neighbourhood name	Area, ha	Population, approx.
Marių	Žardės	1267.57	950
	Smeltės	603.48	51 400
	Lypkių	821.03	60
Baltijos	Gedminių	464.49	45 100
	Rumpiškės	453.74	18 620
Pajūrio	Centro	514.51	17 060
	Melnragės	708.05	1 220
	Smiltynės	774.72	80
Danės	Sendvario	569.66	4 160
	Luizės	492.28	10 060
	Tauralaukio	806.97	2 720
	Labrenčiškių	1356.66	5 980

### 3.1 Creating GIS Database

We used GIS and PYTHON scripting language to process the data. The most challenging step was to create the proper GIS database.

In our case study we used more precise data than land cover images. In town planning practice the huge areas of 500x500 m doesn't make a difference, all changes usually take place on micro level. For location based calculations the urban structure must be divided into finite elements.

Very often at this stage researchers use the readily available data from CORINE land cover or other satellite image based sources. The common practice is to use raster cells or just divide the land cover polygons by rectangular mesh and assign to the produced cells the weights according to the area they have.

This study cannot be directly called "land use mix" because we operate with more precise data than land plots. It is mix of urban functions that is

actually calculated from land cells or parcels, but in most cases the urban activities are concentrated and take place in non-moving part of urban structure – the buildings. In our study we choose time-consuming but still the most practical way to divide urban structure into smaller elements, where each element represents the building of the city. This is most precise technique and only such data can give useful results at smaller scale.

We defined three constant and clear functionally different objects (land-uses) used by transportation planners. These are:

1. Living places (each building was given a number of people living in it);
2. Working places (each building was given a number of people working in it);
3. Places of public attraction (each building was assigned a number of people visiting it in their daily activities different from going home and going to work).

To define the location and number of living places we marked all individual houses and assigned the mean value from Lithuanian National Department of Statistics. For multifamily houses we calculated the number of flats and multiplied it by the value of mean person per dwelling obtained also from official statistics.

To collect data of working places we used register of companies, but the data had to be corrected by the people working at home (around 7% of working people) and other means to get the actual 78 000 working places.

The most challenging task was to collect the number of visitors in the objects of public attraction. This data is very dynamic and there are innumerable attractions inside the city, we used the most significant objects like retail centres, public buildings, other known places which attract more than 100 people per day. This part of the database can be filled and updated with smaller objects to make more precise calculations.

The prepared GIS database contains 17 680 objects, where population is mostly concentrated in multifamily neighbourhoods (Gedminų, Smeltės), working places are mostly concentrated in city center, in the sea port area and business zone in eastern part of the city, and places that attract public are concentrated in Gedminų neighbourhood where there is a biggest population density and also significant part in the city centre. It is worth to notice that some single family housing districts (Tauralaukio, Sendvario, Labrenčiškių) have very few objects of public attraction.

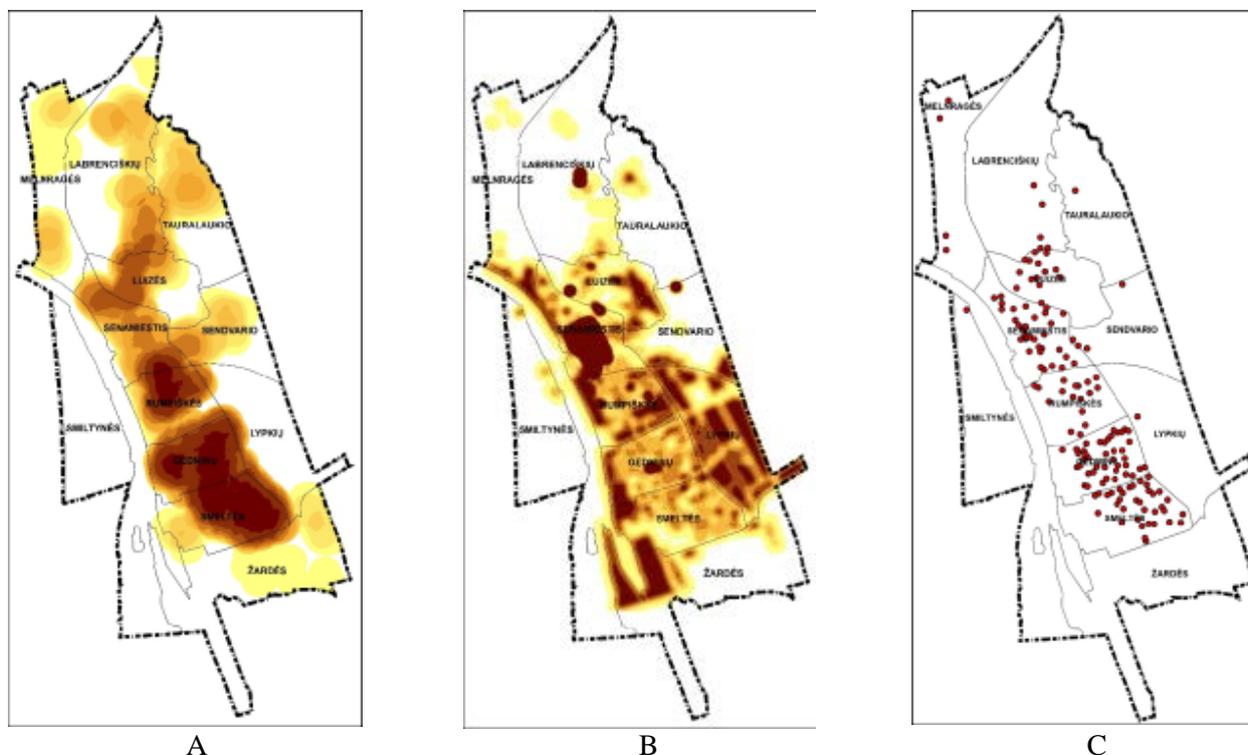


Fig.2 The diagrams showing Klaipėda city GIS model data prepared for evaluation (A – population density, B – density of working places, C – most significant objects of public attraction)

### 3.2 Calculation Algorithm

We used the most common GIS software for developers (QGIS) and PYTHON scripting

language to process the data. Although developed method can easily incorporate most of the methods described in chapters 2.1 and 2.2, we used simple method of ratio values. It was assumed that each pair of functions has its own best ratio, it is the pairs of different objects are:

- Living – Working places 1 : 0.65
- Living – Attraction places 1 : 1
- Working – Attraction places 1 : 1

For planning purposes we calculate all types of mixing – mixing between living-working places (mix\_LW), mixing between living- attraction objects (mix\_LA), mixing between working-attraction objects (mix\_WA) and overall mixing of functions (mix\_SUM). In the text of the script the values i\_mix\_LW, i\_mix\_LA, i\_mix\_WA stand for temporary iteration values to be added to the final sum. The coefficient k is used for distance adjustment - in this example we assume that the distance from 0-200 meters is ideal and the interaction between objects with different functions is most likely to happen, therefore k is assigned max value 1.0. Then from 200-700 m distance is considered the distance for possible interaction in degree with linear dependence to the increasing distance. At 700 and more meters the possibility of interaction is equal to zero.

The script for the calculations was written in PYTHON. Here the function to define mixed use level at one separate cell is presented. The arguments passed to the function are cell centroid coordinates (x, y) and the numbers of living, working places and public attraction ratio in it. For the “list\_of\_objects” here stands global array of all other city objects. The script has many “if” statements to avoid division by zero and to find symmetrical ratio between two numbers.

```
def MIX_LEVEL(x,y,living,working,attraction):
```

```
##### Initial values are set
```

```
mix_SUM = 0.0
mix_LW=0.0
mix_LA=0.0
mix_WA=0.0
```

```
#####The iteration cycle begins
```

```
for object in list_of_objects:
```

```
#####calculate living-working ratio
```

```
if (living==0) or (object.working==0):
    i_mix_LW=0
elif living<object.working*0.65:
    i_mix_LW=living/object.working*0,65
else:
```

```
i_mix_LW=object.working*0.65/living
```

```
#####calculate living-attraction ratio
```

```
if (living==0) or (object.attraction==0):
    i_mix_LA=0
elif living<object.attraction:
    i_mix_LA=living/object.attraction
else:
    i_mix_LA=object.attraction/living
```

```
#####calculate working-attraction ratio
```

```
if (working==0) or (object.attraction==0):
    i_mix_WA=0
elif working<object.attraction:
    i_mix_WA=working/object.attraction
else:
    i_mix_WA=object.attraction/working
```

```
#####After ratios were calculated
```

```
#####it has to be multiplied by distance coefficient
```

```
#####in this example we use formula
```

```
#####for distance covered by foot - 700 m
```

```
dist=distance(x,y,object.x,object.y)
```

```
if dist<=200:
```

```
    k=1
```

```
elif dist<=700:
```

```
    k=(700-dist)/500
```

```
else:
```

```
    k=0
```

```
mix_LW+=i_mix_LW*k
```

```
mix_LA+=i_mix_LA*k
```

```
mix_WA+=i_mix_WA*k
```

```
mix_SUM+=mix_LW+mix_LA+mix_WA
```

```
#####Here the iteration cycle ends
```

```
return mix_SUM, mix_LW, mix_LA, mix_WA
```

The presented algorithm can be easily adopted to work with other types and subcategories of data. It can be extended by implementing more complex indexing between functions (see chapter 2). The distance function can be changed to function that calculates actual paths of travel and returns real distances from the objects. There are many ways to improve the method, but scientific novelty and key points of it lies in:

- Clear definition of functions and relations between different types of functions.
- Consideration of human scale distances – the point which is missing in most other case studies.

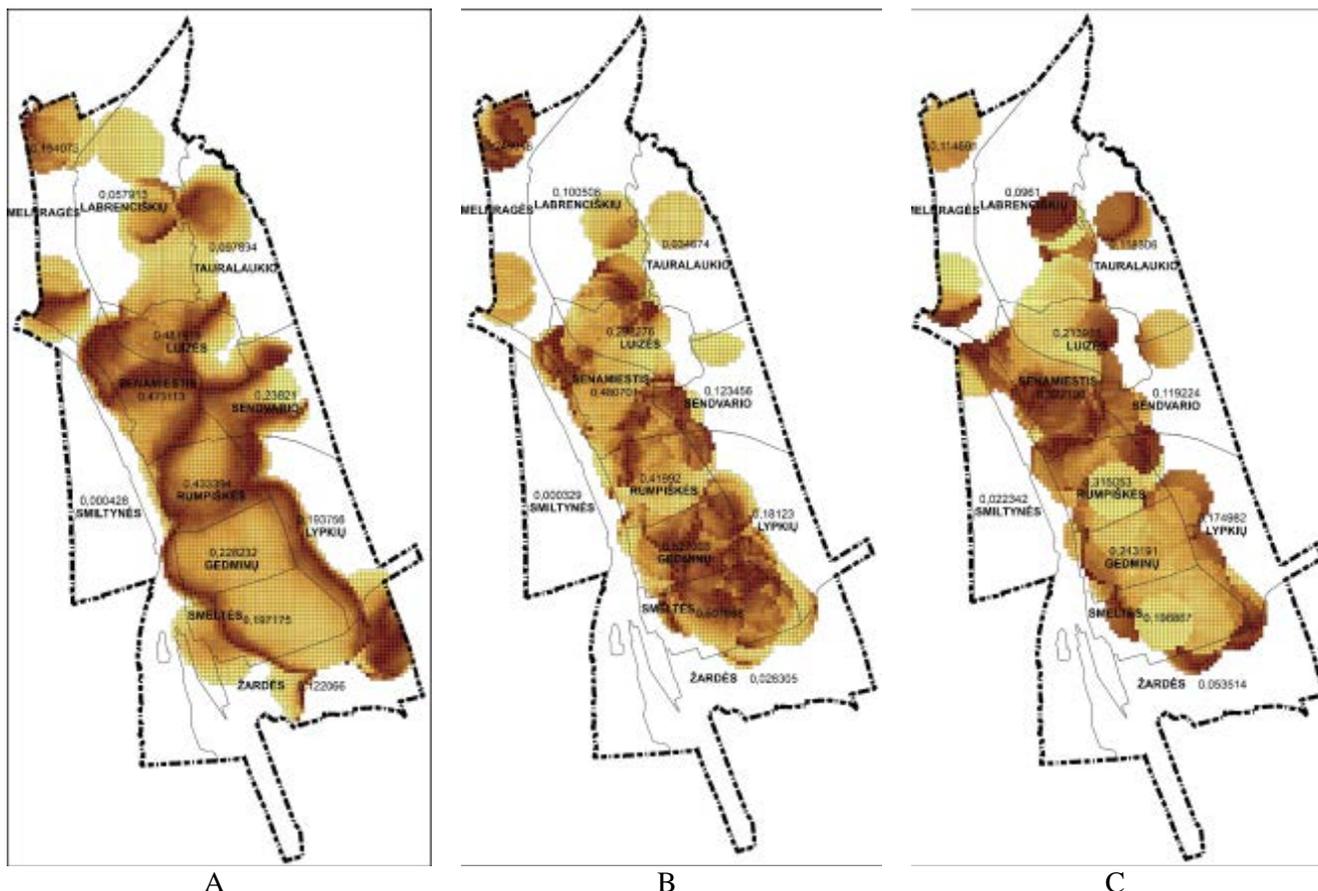


Fig.3 The diagram of mixed-use level index between: A – living places and working places, B – living places – places of public attraction, C – working places – places of public attraction.

### 3.2 Results of Performed Estimation

Calculated values were passed to attribute table of GIS objects. The diagrams were created (Fig.3) to show the most and least mixed areas between three different pairs of functions. Examination of such diagrams gives clear insight of sustainability and object location problems to the planner.

From diagram A comes conclusion that the mix of living-working places is the best on the edges of mono-functional multifamily living districts. However it is the worst inside these districts.

Mix between living-attraction objects is the best in historical town centre, new centre and in Smiltės and Gedminių neighborhoods. It is very low in single family housing areas with low population densities.

Mix between working-attraction objects is the best in historical town center. In other territories it is quite low.

Overall level of mixed uses (fig.4) depicts the most problematic mono-functional areas and these are, not surprisingly, areas of multi-family living districts built in modernist era and areas of recently developed suburban single family housing. It also shows that only the central district has the proper mix of all three functions.

Knowing the “white spots” of the worst areas the planner and decision maker can find the best places and functions for new development.

The overall mean values for the different neighborhoods are shown in Table 2.

Table 2 The degree of mixing the uses for the neighbourhoods of Klaipėda city

Name	Rating	LW	LA	WA	SUM
Žardės	11	0.12	0.02	0.05	0.20
Smiltės	4	0.19	0.50	0.19	0.90
Lypkių	6	0.19	0.18	0.17	0.54
Gedminių	3	0.22	0.62	0.24	1.09
Rumpiškės	2	0.43	0.41	0.31	1.16
Centro	1	0.47	0.48	0.52	1.47
Melnragės	7	0.15	0.24	0.11	0.51
Smiltynės	12	0	0	0.02	0.02
Sendvario	8	0.23	0.12	0.11	0.48
Luizės	5	0.48	0.28	0.21	0.82
Tauralaukio	9	0.09	0.03	0.11	0.25
Labrenčiškių	10	0.05	0.10	0.11	0.25

One of the worst neighborhoods in terms of mix of function (Tauralaukio) was examined more closely. Since this neighborhood is built up mostly

by single family houses and 2 storey buildings the proposals for micro-insertions of small buildings with missing functions were given (see Fig. 5). The proposals were given to add blocked family houses, small multi-family houses, locate few small business enterprises, small daily market. It was observed that there is no kindergarden in district which has more than 2000 inhabitants, so the proposal was given to add this small object that contributes greatly to the mix of uses. As a result the neighborhood can become more compact, sustainable and walkable. After adding new objects the calculation was performed again and Fig.6 and Table 3 shows significant improve of mixing levels.

Table 3 The degree of mixing the uses for the Tauralaukio neighbourhood before and after supposed measures

	LW	LA	WA	SUM
<b>Before</b>	0.09	0.03	0.11	0.25
<b>After</b>	0.13	0.12	0.14	0.38

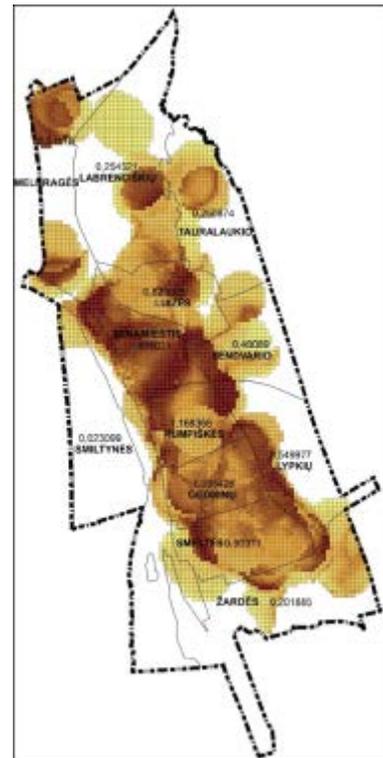


Fig.4 The diagram of overall mixed-use level index for Klaipėda city

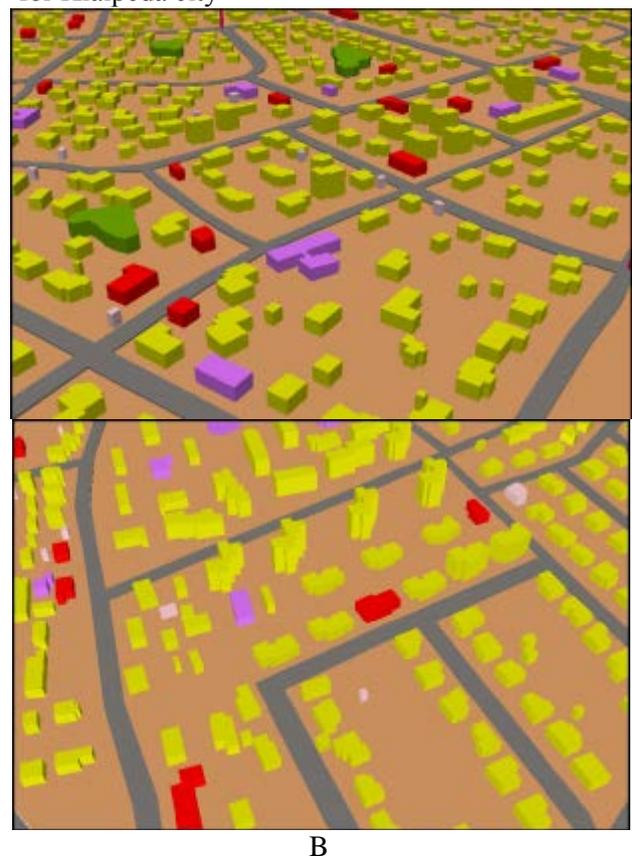


Fig.5 The solutions to improve the level of mixed use in Tauralaukio district of Klaipėda city (A – existing situation; B – proposals for micro-insertions)

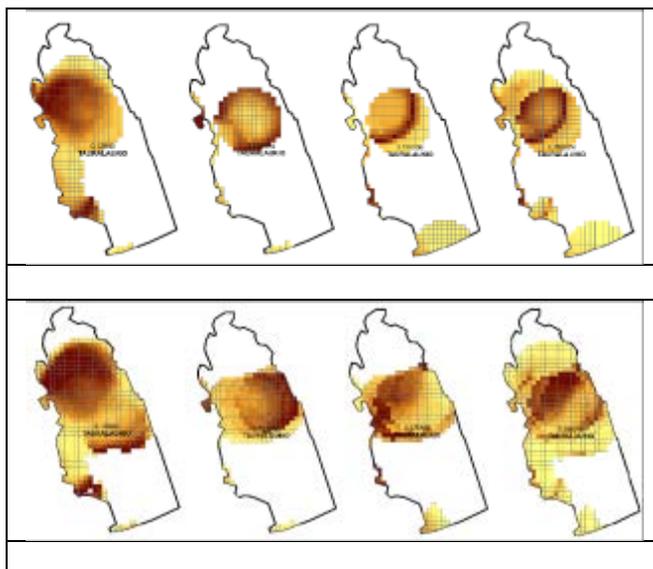


Fig.6 The calculated change of function mixing levels in Tauralaukio district of Klaipėda city after proposed development

#### 4 Conclusion

Mixed-use development is most important issue of urban sustainability. Although it is the key principle for sustainable development and is frequently mentioned in urban literature, it is rarely elaborated upon with substantive and empirical support.

Recent research is often based on inaccurate databases taken from readily available sources such as satellite images. The term “land use mix” is incorrect by itself because actual interaction is between people living, working and fulfilling other daily activities in the city. To measure the possibilities of these interactions more precisely the data must be based on smaller scale objects – the buildings. Presented example show the advantage of such database.

The standard mathematical models and methods for quantifying mix parameter in most recent researches come from social geography sphere and miss the planning goals and human scale. These studies are meant mostly for statistical comparison. To add human scale researchers must be very sensitive with the distance factor. The demonstrated mathematical model works with precise data and adds human dimension when considering possible interactions between objects. The presented schemes show the walkability of the analysed area and prove the importance of scale factor.

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