Risk Analysis: A Focus on Urban Exposure Estimation

Roberto De Lotto, Caterina Pietra, and Elisabetta M. Venco(✉)

DICAr, University of Pavia, Via Ferrata 3, 27100 Pavia, Italy
{uplab, elisabettamaria.venco}@unipv.it

Abstract. In risk analysis, extremes natural phenomena become hazardous when they strike human beings, tangible and intangible assets. In urban areas, the exponential growth of population and its density makes cities more exposed to the effects of natural impacts that could become catastrophic and generate high-risk situations. As a result, the current situation makes the population and its economic and social activities highly exposed to the different natural risks. In the last 40 years, the Exposure of built-up area and population to natural hazards doubled: now seismic hazard could affect 2.7 billion, volcanoes eruptions 414 million people and tropical cyclones over 1.6 billion.

Authors consider Exposure as the quantity and quality of the different anthropic elements (population, settlement system, infrastructure network, elements of the environment) of a given territorial area and whose conditions and operation can be damaged, altered or destroyed by natural hazards. Therefore, the exposure assessment of the different urban functions becomes the basis for implementing risk reduction interventions. The presented research defines a methodology to study the location and distribution of population (spatial and temporal dynamic entity), the different urban functions, human assets and their activities. In particular, authors analyze the statistical possibility that human beings are in an area at risk in a well-defined period of time (24 h a day, 7 days a week and 365 a year). It depends on city structure, functions distribution, its widespread elements and through these elements authors estimate Urban Exposure.

Keywords: Urban Exposure · Natural risks · Parameters estimation

1 Introduction

Nowadays, natural hazards have huge social and economic impact in urban areas because urbanization and economic development increase people and assets' concentration in high-risk prone areas. The intensification and diversification of land-uses (especially in low-income and developing countries) lead cities to be exposed to multiple effects of different types of natural hazards. A natural event is a potential threat to human life and property: it become disaster or catastrophe when human beings (and their physical and economic assets) live or work in its path. Consequently, hazards generate risks in relation to population and its physical and economic assets' Exposure [1].

© Springer Nature Switzerland AG 2019
S. Misra et al. (Eds.): ICCSA 2019, LNCS 11620, pp. 407–423, 2019.
https://doi.org/10.1007/978-3-030-24296-1_33

The Atlas of the Human Planet 2017 [2] highlights how the Exposure of built-up area and population to natural hazards doubled in the last 40 years. Seismic hazard accounts for the highest number of people potentially exposed (from 1.4 billion in 1975 to 2.7 billion in 2015). In 2015, 414 million people lived near one of the 220 most dangerous volcanoes. Flood, the most frequent natural disaster, potentially affects more people in Asia (76.9%) and Africa (12.2%). Furthermore, population exposed to tropical cyclones increased from 1 billion in 1975 up to 1.6 billion in 2015 and 45 countries are exposed also to devastating hurricanes. Moreover, in according with that research, the country most at risk to tsunamis is Japan. Finally, sea level surge affects the countries across the tropical region and China has one of the largest increase of population: plus 200 million people from 1990 to 2015.

As many authors define, Exposure means the quantity and quality of the different anthropic elements of a given territorial area whose conditions and operation can be damaged, altered or destroyed by natural hazards [1, 3–8].

In particular, quantity means number of buildings, people or activities; quality means functional/strategic aspects, i.e. existing relationships between physical elements and territorial systems; anthropic elements mean population, settlement system, infrastructure network.

So the dimensions involved are:

- physical dimension, relative to the quantity of goods or persons exposed in the territory;
- functional dimension, relative to the functional role (strategic, economic, historical-cultural heritage) of the physical elements exposed in the territory.

Given the extremely heterogeneous nature and the amount of information and elements to consider, the definition of a general and systematic method is fundamental. For the physical dimension it is possible to identify easily the main characteristics (through classical geographical analysis); for the functional dimension it is not so easy: to understand the functional role of the exposed elements it is necessary to consider, analyze and study the territory itself, its structure and the evolution over time of the relationships existing among each specific part. Therefore, the three macro-categories of elements potentially exposed to risks are:

- Population: resident population and city users (employed, students, users of over-local interest services, tourists)
- Physical elements: housing, cultural/monumental building heritage, strategic and collective interest equipment, mobility and technology networks
- Economic activities: productive and industrial.

The main analysis scales involved are [6]:

- Global scale with statistical information related to the distribution of goods in the considering territory (national/regional/metropolitan/urban level). The use of satellite images and cartographic maps allows the definition of urban density values (m^3/m^2);
- Local scale with databases that provide information at the municipal level (urban blocks and specific buildings). The type and building function (residential,

commercial or tertiary) analysis is fundamental: over time and in space the Exposure values of the related category derives from it. Data (percentage and the gross floor area - GFA of each urban function, number of floors of each building) collection is made through cartographic systems and, if necessary, direct *in-situ* survey. The number of people in a specific urban function derives from the definition of crowding.

In particular, for the population category, it is fundamental using a multi-scale evaluation and considering temporal, spatial, dimensional and functional variables.

2 Exposure

2.1 Urban Exposure at Global Scale

Many cities with a strong emerging economy and rapid urbanization, are protagonists of sprawl phenomena that determine the emergence of areas heavily exposed to risks since they were not properly designed and managed. Some of the effects on Exposure arising from urbanization are found at the micro scale, which means at the neighborhood, block or even a single dwelling level, but most of the times the effects fall on all those areas of new and uncontrolled making.

Urbanization, considered as territorial and social organization, can increase the capacity to react, manage and overcome situations of risk and calamitous events. Indeed, the high building and infrastructure density allows an efficient implementation and faster and more specific operations for the establishment of preventive measures. Services related to the management of emergencies can act more easily and achieve a greater number of users who, together with the public part, contribute increasing the resilience and the ability to overcome the event.

Assuming that the risk appetite of a country or a city depends not only from the magnitude of the disastrous event but also and above all from the elements exposed and from the level of development of the society, the final risk index turns out to be a function of Exposure, vulnerability, adaptability and response capability to the event. “Whether it be an earthquake or a tsunami, a cyclone or floods, the risk of a natural event turning into a disaster always depends only partly on the force of the natural event itself. The living conditions of the people in the regions affected and the options available to respond quickly and to provide assistance are just as significant. […] Countries that see natural hazards coming, that are preparing for the consequences of climate change and are providing the financial means required will be better prepared for the future” [9].

In WorldRiskReport 2018 [10], urban Exposure map (Fig. 1) shows highs levels in Central America and in the Caribbean areas, in some states on the Pacific coast of South America, in South-East Europe and Asia, in Japan and Oceania. It is important to note that Japan, the Netherlands and Chile “which rank at 5, 13 and 14 respectively in terms of Exposure, show that even a very high Exposure does not necessarily imply a very high risk”. African countries and some Asian states are less exposed but more vulnerable because of the low presence of potentially destructive phenomena or of large and numerous conurbations.

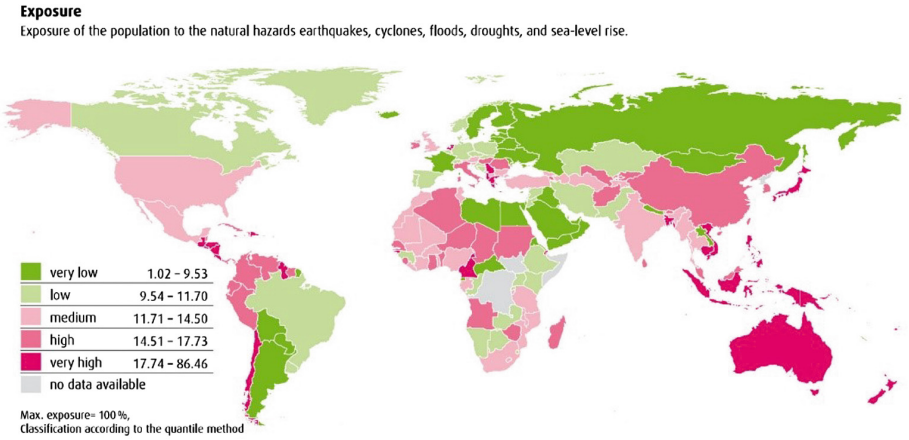

Fig. 1. World Exposure to natural hazards (WorldRiskReport 2018).

Loss Estimated Method. Among all, in traditional engineering models, the estimation of the expected losses in a site is determined by the following equation [11]:

$$\text{Physical Loss} = \sum_{Bk}\left[\left(\sum_{Ii} P(I_i|B_k\right) * \left(\sum d_{rj}P(d_{rj}|I_i, B_k)(d_{rj}|B_k)\right) * V_{Bk}\right] \quad (1)$$

Where:

B_k typology of buildings k;
I_i level of intensity i of the event;
D_{rj} level of the damage expected j;
V_{bk} value of all the buildings of b_k typology;
the sum related to d_{rj} represents the expected damage value for an intensity I_i and for buildings of B_k typology;
the product of this level of damage and the value of all the buildings of b_k typology get the expected loss for the buildings b_k;
the sum respect all the typologies of buildings b_k gives the total expected loss.

It is also interesting the approach for the calculation of Exposure and expected losses that does not use the collected data, but macroscopic indicators: the gross domestic product (GDP) with the underlying assumptions that the number of buildings and artefacts is directly proportional to the social wealth and therefore to the GDP of the region. It follows that the expected physical losses are calculated directly; for a given area or region with a known GDP value [11]:

$$\text{Physical Loss} = \sum I_j\left[P\left(I_j\right)\text{MDF}\left(I_j\right)\text{GDP}\, g(\text{GDP})\right] \quad (2)$$

Where:

$p(I_j)$ probability that the event I_j manifests during the next years;
$MDF(I_j)$ damage factor that represents the relation danger-Exposure-loss in case of event of intensity I_j;
g(GDP) function to correlate GDP with the real social prosperity: it is 5 for regions with high-income economies, 4 for regions with medium-income economies and 3 for China, Japan and India.

2.2 Urban Exposure at Local Scale

At urban scale, the Exposure assessment of the different urban functions (residences, commerce, tertiary, strategic services, road, social and economic infrastructures) becomes essential because of the concentration (density) of people.

To achieve this goal, it is essential to study the localization and the distribution in time and place of population (whose characteristics and behaviour during day and year characterize it as a dynamic and non-static entity), different urban functions, assets and human activities in order to know the real quantity of people that can be affected by events in a certain portion of territory (urban block and neighbourhood).

Authors define the Exposure function of each single urban function in relation to the urban block, the municipal territory or the spatial domain considered (trans/interscalarity) [7, 8, 12] as *f* (people, urban function, population age, hours of functions use, functions m^2):

$$E = \sum \text{age}\left\{\left[\left(\text{u.f. } m^2\right)/(\text{p.d.})\right]/\text{people} \times \left[\left(\text{u.f. } m^2\right)/\left(\text{tot } m^2\right)\right] \times C_{age} \times \text{hours/year}\right\} \quad (3)$$

Where:

u.f. urban function (residential, commercial, tertiary);
p.d. population density; for the residential unit it is considered 50 m^2/habitant, for commercial and tertiary it can be estimated a percentage of the overcrowding index;
age: the population is divided into 3 age groups – children 0–18 years old, adults 19–64 years old and elderly/seniors over 65, already retired;
C_{age}: correction factor based on the population age and on its capacity of not be damaged (i.e. motor skills), calculated by pairwise comparison responding to the question "Which age group is more exposed to risks?";
hours: number of hours of use of an urban function during a year;
m^2: square meters of the single urban function and of the block taken into account;
total number of people: residents and city users of the block taken into account.

Specifically, for the definition of urban Exposure, it is necessary to implement an analysis of urban built-up, through GIS tools, direct surveys and inspections. In particular:

- Definition of building density for urban blocks (it is considered 0–5 m^3/m^2 for low density, 5–10 m^3/m^2 for medium density and > 10 m^3/m^2 for high density) [13, 14];

- Study of the morphology of fabrics (historical, consolidated, open, expansion areas, brownfields, isolated buildings, for mixed activities, for productive activities, for commercial activities, for recreational activities, for services…) [13, 14];
- Definition of areas and percentages of urban functions (residential, commercial, tertiary) for each block;
- Calculation of the crowding index (150 m^3 gross volume/inhabitant[1] for the residences; from the UNI 10339 standard it is considered 0.25 persons/m^2 for the commercial function and 0.1 persons/m^2 for the tertiary)[2] [15].

Once the urban Exposure has been defined, the process goes on with the identification of the types of danger present in the territory through the overlapping of the hazard maps in order to define the most at risk areas and then carry out the evaluation process.

3 Application of the Urban Exposure Function

The urban Exposure calculation function has been analyzed to determine the best possible combinations for block of functions and population in order to reduce Exposure. It is emphasized that to different data on the use of urban functions will correspond different values of Exposure.

Urban settlement areas are characterized by ever-present constitutive elements that determine physical and social form and structure: urban fabrics, collective places and functional mix. Analyzing the city through the study of urban fabrics makes it possible to read the structural conditions of the settlements and the occupation of the land. The following types of fabrics can be found in a small and medium-sized European urban context: historical, consolidated, high density mix, high density mix with production activities, open with medium density, low residential density.

Authors present two case studies that reproduce the situation of a new hypothetical monofunctional residential expansion and an area of functional mix similar to a consolidated context of city center: 10000 m^2 of buildings in a city block 80 × 80 m^3, different functional mixes and crowding indexes. Therefore, they calculate the related Urban Exposure [12].

3.1 Case A

The example presented now considers the 100% residential function and the maximum commercial and tertiary crowding index.

Tables 1 and 2 show the first phase of data entry and the state of affairs to determine urban Exposure at time t = 0. In particular, it reports data concerning areas (m^2)

[1] Average value in new buildings according to Italian urban laws.

[2] The productive/industrial sector are not evaluated, since they are no longer present in the urban fabric of most Italian cities, same for the strategic services (i.e. hospitals and schools) because they are regulated by specific and restrictive risk reduction rules.

[3] It is the classical historical cities block deriving from ancient Roman camp grid.

related to the different functions, the urban density, the number of residents in the territory differentiated by families and age classes and the number of users of commercial and tertiary function. Furthermore, for the tertiary and commerce, a preliminary maximum crowding index is used.

Table 1. Data entry: different functions m^2 and indexes.

Areas (U.F.)				Urban Indexes		
Residential R (m^2)	Commercial C (m^2)	Tertiary T (m^2)0	Total (m^2)	R m^2/ inh	C m^2/ inh	T m^2/ inh
10.000	0,00	0,00	10.000	50	4	10
%			%			
100	0	0	100			

Table 2. Data entry: inhabitants.

People						
R (inh)	C (inh)	T (inh)0	Tot inhabitants	Families	Elderly for each family	Children
200	0	0	200	0,25	0,8	0,7

Table 3 shows data referring to the people present in the different urban functions (always taking into account the age class) and the hours of use of these ones during the day compared to the year (it is therefore an average of the presence of people in the urban functions based on work, leisure time, main activity etc.) [16].

Table 4 reports daily hours during which people are not present in the three urban functions studied (they can therefore be in service structures, in open spaces or on means of transportation).

The different combinations tested (summarized in Table 5) show clearly how a homogeneous functional mix within the sector allows to obtain very low Exposure values since the population is not maximal in the residence (it is considerably reduced the Exposure during night hours) and equally distributed throughout the day between the tertiary and commercial sectors (both for work and leisure).

The lowest results are achieved by minimizing the commercial sector: once fixed the square meters of area and the crowding indexes, in the case of 50% residential and 50% tertiary, the overall Exposure is equal to 124 due to the considerable presence of people also in the tertiary (there are 100 people in the residential function and 500 in tertiary). With a functional mix that sees the residential at 60%, the commercial sector at 10% and the tertiary at 30%, the Exposure value reaches its minimum equal to 62.

The last case determines a number of people equal to 120 for the residential function, 250 for the commercial and 300 for the tertiary: the creation of the functional mix with very low values of the commercial reduces the presence of people (for leisure and for work) within the sector. On the other hand, the increase of the residential part makes the Exposure greater at night and so a greater number of people exposed to risk.

Table 3. Project data entry: urban functions times of use.

Residential R					Commercial C					Tertiary T				
Families	Adults for each families	Children	Adults	Elderly	Families	Adults for each families	Children	Adults	Elderly	Families	Adults for each families	Children	Adults	Elderly
50	100	40	120	40	0	0	0	0	0	0	0	0	0	0
		14	9,75	16			2	5	2			1	4,5	1
Hours/year		204.400	427.505	233.600	Hours/year		0	0	0	Hours/year		0	0	0

Table 4. Project data entry: times of use of urban functions other than Residential, Commercial and Tertiary.

Δ Hours a day			
Children	Adults	Elderly	
4	4,75	5	Hours a day
8760			Hours a year

Table 5. Different mix of urban functions and calculation of urban Exposure for each category of users.

% Resid.	% Comm.	% Tert.	Children	Adults	Elderly	Total
100	0	0	187	146	240	573
0	100	0	333	938	375	1646
0	0	100	67	338	75	480
50	50	0	80	220	92	392
50	0	50	22	76	26	124
0	50	50	64	192	73	328
33	33	33	28	81	32	141
60	10	30	15	27	20	62

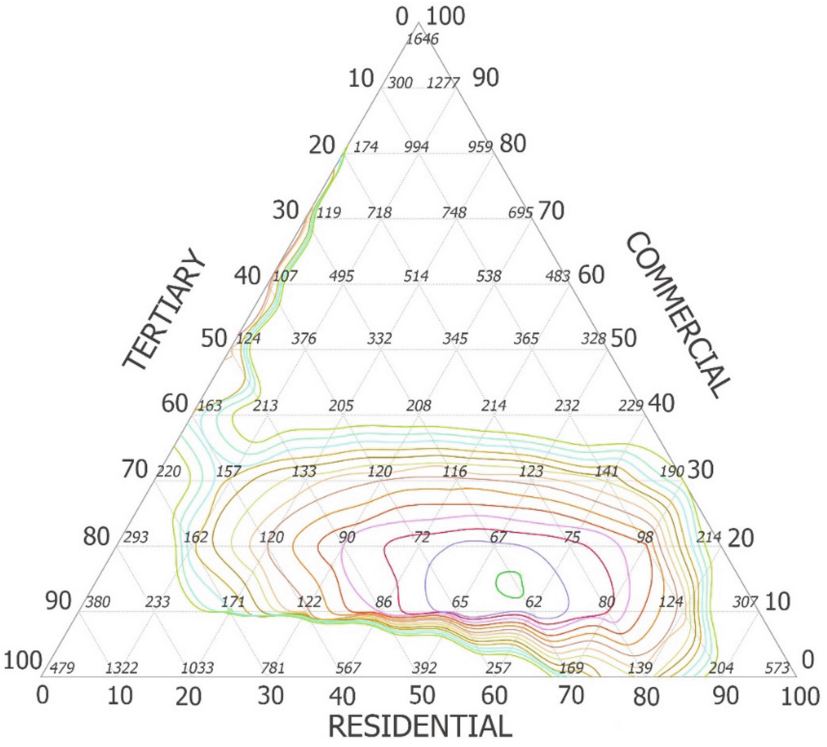

Fig. 2. Graphical representation of urban Exposure in relation to the different urban functions mixes.

From a graphical point of view, the operations described above are represented in Fig. 2.

The graph in Fig. 2 derived by placing the urban functions' percentages (residential, commercial and tertiary) on the sides of the triangle, while the numbers shown inside are the actual Exposure values that are obtained based on the functional mix of reference.

For example, considering 100% residential is obtained a total Exposure of 573; with 50% residential and 50% tertiary, is obtained an Exposure of 124; with 10% residential, 60% commercial and 30% tertiary, the result is a total Exposure of 495; with 60% residential, 30% commercial and 10% tertiary, the result is 141; and so on.

Once the basic grid has been constructed, the different curves representing the Exposure values have been defined (Fig. 3): they are effectively level curves (in this case, they can be called Exposure Curves) because join points with the same Exposure.

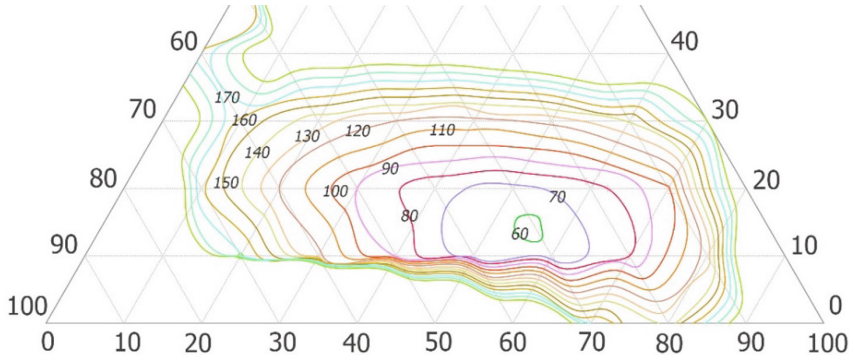

Fig. 3. Graphical representation of urban Exposure in relation to the different urban functions mixes: detail of the Exposure Curves and their value (from 60 to 170).

The last step concerns the identification of the minimum Exposure value (Fig. 4):

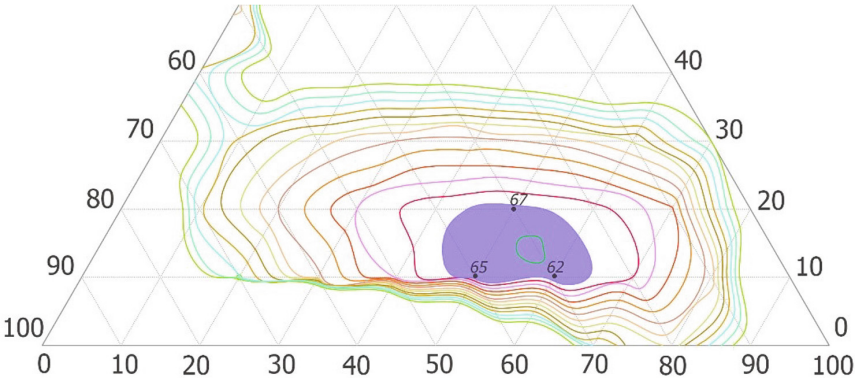

Fig. 4. Graphical representation of urban Exposure in relation to the different urban functions mixes: in evidence, the area with an Exposure value less than or equal to 70.

3.2 Case B

It is presented now the case with the crowding index of the commercial and tertiary function equals to 14 m^2/user[4] (user means both the employee and the person who takes advantage of the function) considering also a functional mix equal to 50% residential and 50% tertiary.

The index of commercial and tertiary use equal to 14 m^2/users determines that a homogeneous functional mix leads to lower Exposure values because the population is not maximized in the residence (thus the Exposure at night is considerably reduced) and, then, equally distributed throughout the day between the tertiary and commercial sectors (both for work and leisure) (Tables 6, 7, 8, 9 and 10).

From a graphical point of view, the operations described above can be represented as follows also with the lowest Exposure values (Fig. 5).

Table 6. Data entry: different functions m^2 and indexes.

Areas (U.F.)				Urban indexes		
Residential R (m^2)	Commercial C (m^2)	Tertiary T (m^2)0	Total (m^2)	R m^2/inh	C m^2/inh	T m^2/inh
5.000	0,00	5.000	10.000	50	14	14
%			%			
50	0	50	100			

Table 7. Data entry: inhabitants.

People						
R (inh)	C (inh)	T (inh)0	Tot inhabitants	Families	Elderly for each family	Children
200	0	0	200	0,25	0,8	0,7

[4] In Italy, this value is often used in the analyses carried out by the Municipalities for the average calculation of the users of the specific sector.

Table 8. Project data entry: urban functions times of use.

Residential R					Commercial C					Tertiary T				
Families	Adults for each families	Children	Adults	Elderly	Families	Adults for each families	Children	Adults	Elderly	Families	Adults for each families	Children	Adults	Elderly
25	50	20	60	20	0	0	0	0	0	89	178	71	214	72
		14	9,75	16			2	5	2			1	4,5	1
Hours/year		102.200	213.525	116.800	Hours/year		0	0	0	Hours/year		25.915	351.730	26.280

Table 9. Project data entry: times of use of urban functions other than Residential, Commercial and Tertiary.

Δ Hours a day			
Children	Adults	Elderly	
4	4,75	5	Hours a day

Table 10. Different mix of urban functions and calculation of urban Exposure for each category of users.

% Resid.	% Comm.	% Tert.	Children	Adults	Elderly	Total
100	0	0	187	146	240	573
0	100	0	95	267	108	470
0	0	100	47	241	54	342
50	50	0	29	60	34	123
50	0	50	19	55	24	98
0	50	50	18	65	20	102
33	33	33	9	26	12	47
60	10	30	22	27	28	77

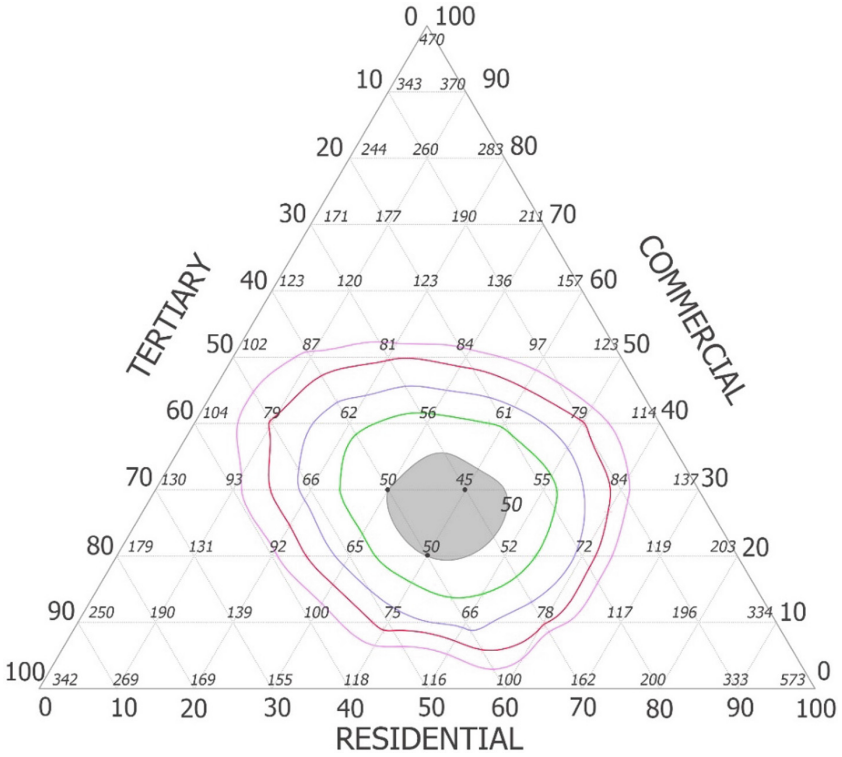

Fig. 5. Graphical representation of urban Exposure in relation to the different urban functions mixes: detail of the Exposure Curves and their value (from 50 to 90) and, in evidence, the area with an Exposure value less than or equal to 50.

4 Discussion

Starting from the simulations described in the previous chapter, in the comparison between the two different examples emerge some interesting comments regarding the urban distribution of functions. As soon as it is an ideal simulation, even if completely similar to real case studies (at least in the European context), the results must be considered as indicators of the directions and purpose of certain existing situations or planning solutions. So, the evaluation of Urban Exposure can be considered also as an instrument to assess different planning scenario.

For the Case A, the minimum Exposure values are around 60. From the point of view of urban and territorial planning, the 3 points highlighted in Fig. 4 are more interesting because they derive from functional mixes that are easily traceable in an existing fabric or just as easily definable when creating new compartments or relocating functions:

- 50% residential, 20% commercial, 30% tertiary → E = 67;
- 50% residential, 10% commercial, 40% tertiary → E = 65;
- 60% residential, 10% commercial, 30% tertiary → E = 62.

For the Case B, the lowest Exposure is equal to or less than 50. In particular, from the point of view of urban and territorial planning, the most interesting Exposure values are the 3 points highlighted in Fig. 5 that derive from functional mixes easily traceable in an existing fabric or equally easily definable when creating new sectors or relocating functions:

- 40% residential, 20% commercial, 40% tertiary → E = 50;
- 40% residential, 30% commercial, 30% tertiary → E = 45;
- 30% residential, 30% commercial, 40% tertiary → E = 50.

Seek the minimum value of the function (3) leads to define a particular point that can hardly be used and therefore is considered not significant: its use, that define such a limiting range of action, does not allow adequate urban development (the 0.1% variation automatically exceeds the set threshold value).

Considering the values obtained from the application of (3), it is clear that the mono-functionalization of the urban area produces Exposure values even 4 times higher than a functional mix. Furthermore, the presence of both a mono-function and maximum crowding indices leads to high Exposure values. In Case A (Fig. 2), in fact, considering 100% of commerce the Exposure reaches a value of 1646. Obviously, as in Case B, the reduction of crowding indexes greatly reduces the Exposure values: there with the 100% of commerce, Exposure reaches a value of 470 (Tables 11 and 12).

Please note that the present analysis starts from statistical data regarding the population, and from objective data regarding the areas (m^2) of the different functions: therefore, the estimation of the population depends on the maximum or average crowding index and on the hours of estimated use of urban functions. It follows that the values can be amplified and purely indicative.

Table 11. Urban Exposure values in Case A.

Exposure highest values				Exposure lowest values			
Case A	%R	%C	%T	Case A	%R	%C	%T
1646	0	100	0	62	60	10	30
1322	10	0	90	65	50	10	40
1277	0	90	10	67	60	10	30
1033	20	0	80	72	40	20	40
994	10	80	10	75	60	20	20

Table 12. Urban Exposure values in Case B.

Exposure highest values				Exposure lowest values			
Case B	%R	%C	%T	Case B	%R	%C	%T
573	100	0	0	45	40	20	40
470	0	100	0	50	40	30	30
370	10	90	0	52	50	20	30
343	0	90	10	55	50	30	20
342	0	0	100	56	30	40	30

5 Conclusion

The presented research outlines that the population is the most important element to be considered. A fundamental next step will be the study of the real-time behaviour of people during the day and related to the different urban functions through specific surveys with questionnaires and the use of satellite data, Big Data, applications and social tools georeferenced or Wi-Fi tools.

From this point of view, interesting is the development of datasets on population distribution (both as forecasts and as realistic and timely analysis) resulting from the intersection of personal data, postal codes, density, flow of students and workers etc. Among all: Gridded Population of the World (GPWv4), Global Rural-Urban Project (GRUMP), LandScan (with attention to day/night variations on 1 km side grids) [17–19], Open WorldPop (estimation of populations with a spatial resolution of 100 mt 100 mt) [20]; GHS-POP (population distribution from GPWv4 data) [21].

Moreover, the presented graphical representation results effective because it allows identifying the area where the urban Exposure has to be maintained or tended: the value will be proportional to the capacity of the urban system to bear economically and socially the changes behind the achievement of the goal. In urban planning, it is not important reach the minimum of the function because it leads to define a particular point that can hardly be used: such a restrictive range of action does not allow an adequate urban development and the definition of advanced strategies to reduce Exposure and then risks.

It is important to underline that the choice to consider a particular index of crowding (or use, considering both workers and users) produces results of quite different Exposure: the consequences can be reflected on the assessments and choices of the decision makers and planners. This is an aspect that decision makers, public administration, experts and citizens' representatives will have to evaluate according to the characteristics of each urban area (cultural and morphological permanencies, economic and productive activities, etc.), population, external contingencies (current natural risk), economic and welfare and the preparation to develop appropriate plans and strategies to respond in advance to the dangers.

Since that, mitigation actions working on Exposure imply removing, reducing and controlling the quantity and quality of the objects exposed in an area subject to risks: at urban/municipal level, therefore, the Exposure analysis must develop by referring to the areas of expansion and the consolidated fabric.

As outlined in the New Urban Agenda [22] (in relation to Sendai Framework) and in the OECD researches [23] (in relation to the better life index), for a shared Disaster Risk Management it is also necessary to define a common line for the Exposure assessment and estimation in order to produce homogeneous, shareable and easily usable results in the different at risk areas and at different urban scales.

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