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Urban Metabolism Analysis as a Support to Drive Metropolitan Development

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Abstract

The research concerns the topic of urban metabolism as a method to orient policies at urban/territorial level. As suggested by other researches, a metabolic analysis of the urban environment could help planners and managers to improve resource use in cities; to reduce environmental degradation; to identify environmental impacts of energy, material, and waste flows; and to isolate problematic areas in need of attention. The metabolic framework implies a deep knowledge of the main local input and output flows of energy and matter, with detailed energy and environmental accountability. There are thus some difficulties to develop a comparative metabolic analysis of more territories. The research was developed within a wide national academic study in several Italian urban regions and focuses, in particular, a square territory of 100 × 100 km2 around the centre of Milan, in northern Italy. The main local input and output flows are analysed for each municipality (904 in total) considering the available databases. Urban metabolism is investigated by the application of a fuzzy logic model, which consists in a hierarchically organized system of variables and their fuzzy evaluations using a cascade of Takagi-Sugeno models. The overall structure of the model, the definition of the subsystems (built environment, people mobility and socio-economic context in relation to quality of life), the set of the indicators, the adopted benchmarks and the levels of importance of the variables are calibrated on the actual context of application.
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The model provides as synthetic outcome the UEI (urban efficiency index), which is very clear from the point of view of interdisciplinary approach. Therefore, this kind of index can support policy makers, public utilities, urban designers and other stakeholders in defining strategies for improving the performance of the different urban areas looking at their features, weaknesses

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and potentialities. Further, the structure of the UEI underlines the important role of utilities and their effects. This study represents an important occasion for applying the metabolism approach to a well-known territorial context and compare several territories at once.

1. Introduction

Recent European programs[2] look at cities and urban areas as a resource towards social and territorial cohesion and sustainability. At the same time, a city could be seen as a never-ending devouring organism, in terms of soil, raw materials and energy that produce products, services, welfare, etc., as assessed by the founding concepts of urban metabolism developed in '60 -'70 [1, 2, 3] . A metabolic analysis of the urban environment could help planners and managers to improve resource use in cities; to reduce environmental degradation; to identify environmental impacts of energy, material, and waste flows; and to isolate problematic areas in need of attention. Several studies applied the concept of urban metabolism to urban planning and design, as reported in [4], but there are still some issues to be addressed. The urban metabolism approach could highlight some inefficiencies, such as the presence of linear flows that could be made more circular [5]. However, also due to the difficulties to obtain detailed data, very few studies have tried to make the analysis a tool to plan a change in the metabolism of the urban environment [6, 7].

Further, to understand the efficiency of urban metabolism, a comparison among similar cities should be accomplished. However, there are still few cross-sectional studies of multiple cities [8, 9].

Cities are commonly considered as out of equilibrium open complex systems characterized by a high level of internal organization [10]. In this approach, the definition of the correct boundary is fundamental but difficult because often data are available only within the administrative boundaries (municipalities, provinces, regions), while the urban organism could be smaller or larger.

It should also be noted that a city is not a simple biological organism or thermodynamic system, but the resources are used to produce more "human opportunities" [11] and this should be taken into account in the application of a metabolic approach. Therefore, it could be interesting to move towards more interdisciplinary models of urban metabolism [12] that consider not only the material flows but also the liveability and the social aspects of the urban organism.

The research here presented try to investigate some of these issues, starting from the analysis carried out in the framework of the interdisciplinary project "Post-metropolitan territories"[3]. The project was aimed to explore the new urban forms of contemporary Italy, to study the emergence of new "urban questions" and to reflect upon the capacities of these post-metropolitan territories and urban formations to cope innovatively and appropriately with the challenges produced by occurring transformations.

The objectives of the research here presented are:
- to analyse the main local input and output flows for each municipality (904 in total) in the square of Milan;
- to adapt and apply a metabolic model able to evaluate a synthetic urban efficiency index (UEI);
- to provide results easy to read by planners and decision makers through the use of clustering and geographic representation.

2. Materials and method

The authors present an analysis aimed at understanding the metabolic profile at a regional scale and how the whole urban region shows interesting behaviours in terms of production and consumption of energy and resources. This would allow framing the sustainability issue within a new transcalar approach and identifying new challenges for policies. At the same time, exploring fluxes of energy and resources, it is possible to focus geographies that go well beyond traditional metropolitan and city boundaries, linking local and global networks.

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[2] EU Urban Agenda, http://ec.europa.eu/regional_policy/en/policy/themes/urban-development/agenda/
[3] "Post-metropolitan territories as emergent forms of urban space: coping with sustainability, habitability, and governance", www.postmetropoli.it

2.1. Boundary

The research project has assumed constitutively that institutional boundaries cannot be considered as relevant analytical units; therefore, a novel research unit (a square of 100×100 km^2 in every urban area analysed) was defined. This choice permitted to go well beyond the boundaries of the main Italian cities, crossing also the provincial boundaries and going beyond any predefined definition of functional urban area. In particular, among the 9 squares investigated in the research (around the seven cities of Turin, Milan, Venice, Florence, Rome, Naples, Palermo and around the two low-dense areas of South Sicily and North Sardinia), the present work concerns the square of Milan, in northern Italy (Figure 2).

Table 1. Parameters adopted in the application of the metabolic model.

Name	Description	Unit	Inputs	Outputs	Products
EnTrans	energy for transportation	MWh/y inh)	x		
CO2Trans	CO2 produced by transportation	t/(y inh)		x	
NOxTrans	NOx produced by transportation	kg/(y inh)		x	
PMTrans	PM10 produced by transportation	kg/(y inh)		x	
ProzTrans	Prec Oz produced by transportation	kg/(y inh)		x	
GreenMov	Green movement share	%			x
KmCovYear	km covered in a year	km/(y veh eq)			x
MobIndex	Mobility index	%			x
UrbDens	Urban density	inh/km2	x		
HeatRes	Energy consumption for heating - RES	kWh/(m2 Kd y)	x		
WarBuild	Water consumption for buildings	m3/(inh y)	x		
ElectRes	Total electricity consumption - RES	kWh/(m2 y)	x		
RnwEnShare	Renewable energy share	%	x		
FragIndex	Fragmentation Index	-	x		
MunicWaste	Municipal waste	kg/(inh d)		x	
PMHeat	PM10 produced for heating	mg/(m2 Kd y)		x	
CO2Heat	CO2 produced for heating	g/(m2 Kd y)		x	
NOxHeat	NOx produced for heating	mg/(m2 Kd y)		x	
CO2Elect	CO2 produced for electricity	kg/(m2 y)		x	
CO2Waste	CO2 produced for waste	kg (m2 y)		x	
CO2WstWtr	CO2 waste water	kg (m2 y)		x	
ESC	Ecosystem server capacity – ESC	-			x
WasteRecShare	Waste recycling share	%			x
GDP	GDP	€/inh			x
NumJob	Number of job positions	%			x
VulnIndex	Vulnerability Index	-			x
EnIntEcon	Energy intensity of economy	TOE/€			x

2.2. Available databases

The square of Milan is mostly included in the administrative boundary of Lombardy Region. In the national framework, Lombardy excels in terms of database availability. In fact, many interesting data are available for each municipality about energy and environmental issues (i.e. Sirena[4]; Inemar[5]). These datasets were adopted for the

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[4] http://sirena20.energialombardia.eu
[5] http://www.inemar.eu

construction of the metabolic model together with other statistics available for each municipality of Italy (data from Istat[6], census of year 2011). When necessary, other sources such as Eurostat[7], technical literature, data provided by regional technical offices[8] and other information elaborated in the framework of the research "Post-metropolitan territories" were taken into account for the development of the metabolic model.

2.3. Structure of the model

The present work is aimed at defining an urban efficiency index (UEI) taking into account the relationships among urban structure, energy consumption, emissions of pollutants and depletion of resources. According to [10], the performance of the urban system is evaluated splitting it in defined subsystems about mobility and transportation; built environment; socio-economy. The representation through hierarchically organized system of variables and their fuzzy evaluations using a cascade of Takagi-Sugeno models [10] permits the evaluation of the efficiency of these subsystems and the final evaluation of the whole system.

The benchmarks of each parameter adopted in the fuzzy evaluation were calculated in terms of percentiles[9], based on the values assumed by each parameters considering the behaviours of all the 904 considered municipalities. At the end, the synthetic UEI was evaluated. This index is able to grasp the interdisciplinary approach of the research and to support policy makers, public utilities, urban designers and other stakeholders in defining strategies for improving the performance of the different urban areas looking at their features, weaknesses and potentialities.
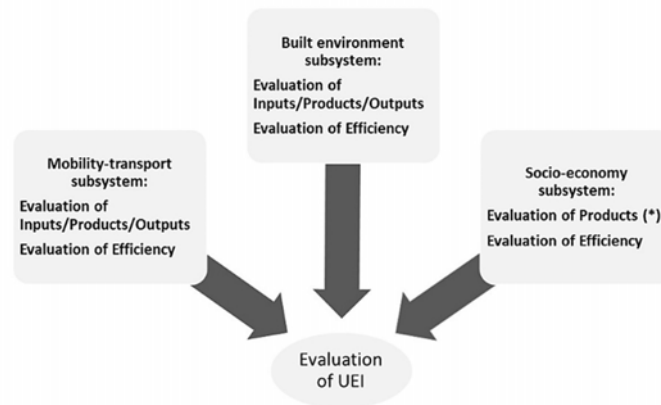

Fig. 1. Scheme of the evaluation of the UEI. (*) the socio-economy subsystem was evaluated in a simplified way according to [10].

3. Results and discussion

The present work focus on the methodological approach and on the types of achievable results rather than on the comments to the outcomes of the elaborations and relative geographic representation for the specific case study.

Data, assumptions and results reported in Table 1 and Figure 1 was recorded for each municipality. Results can be collected in a tabular form in order to carry out statistic evaluations, but parameters, efficiencies and UEI can be also represented by GIS as reported in Figure 2.

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[6] http://www.istat.it
[7] http://ec.europa.eu/
[8] http://www.arpalombardia.it, http://www.ilspa.it
[9] Best = 90° percentile; medium = 50° percentile; worst = 10° percentile if the smaller is the better (i.e. GDP); best = 10° percentile; medium = 50° percentile; worst = 90° percentile if the greater is the better (i.e. fossil energy consumption).
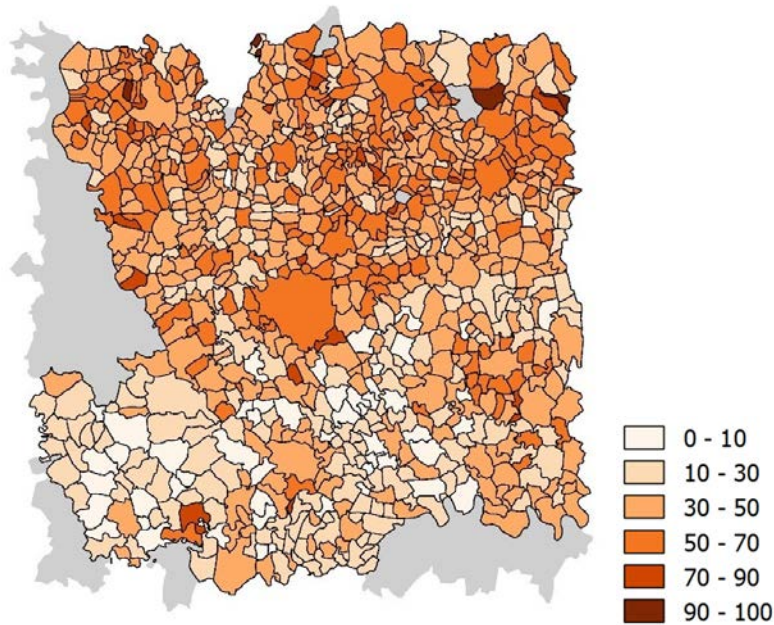
Fig. 2. UEI values for each municipality represented by GIS in a normalized scale from 0 (worst) to 100 (best).

The GIS representation permits a rapid correlation to known local peculiarities (morphology, prevalent economic activity, history and tradition, recent significant modifications, features etc.) that can be rarely be grasped by a mathematic model. Further, it is possible to individuate week areas or performant areas in order to better investigate their features and to orient local policies. This can be easily accomplished due to the GIS representation of all the parameters and of the three efficiencies. Further, sensitivity analysis and simulation of scenarios can be easily accomplished varying the benchmarks and the levels of importance of the parameters considered by the model.

In addition, an automatized clustering procedure was implemented in order to individuate groups of municipality with homogenous efficiencies, using a K-means algorithm [13]. This algorithm converges to a good solution (not necessarily the optimum) given a number of clusters (k). The algorithm output is constituted by k clusters, each of them defined by the centroid of the k subsets of the whole set value distribution of chosen variables.

For example, clustering was implemented taking into account the correlation between UEI and Gross Domestic Product (GDP, Figure 3) and between UEI and urban density. These two parameters were selected in order to explore the sensitivity of the model to the main economic variable and to verify the correlation between urban density and urban efficiency.

The results of the clustering are then represented by GIS in order to easily identify homogenous areas. For example, Figure 4-A reports the map of the clustering reported in Figure 3 considering, in the metabolic model, urban density as the ratio between number of inhabitants and the built surface of the municipality. While Figure 4-B reports the same result considering the urban density as the ratio between number of inhabitants and the total (built and natural) surface of the municipality.

Finally, in order to investigate the capability of the model in the framework of a different approach focused only on energy and environment issues, a new sensitivity analysis was carried out, as reported in Figure 5, where the socio-economy subsystem is neglected (i.e. its level of importance is null). This option attempts to give an answer to the skepticism of urban planners regard the development of a model able to take into account urban complexity and urban people behavior. The attempt demonstrates the possibility to focus the attention of the experts only on selected energy and matter flows.
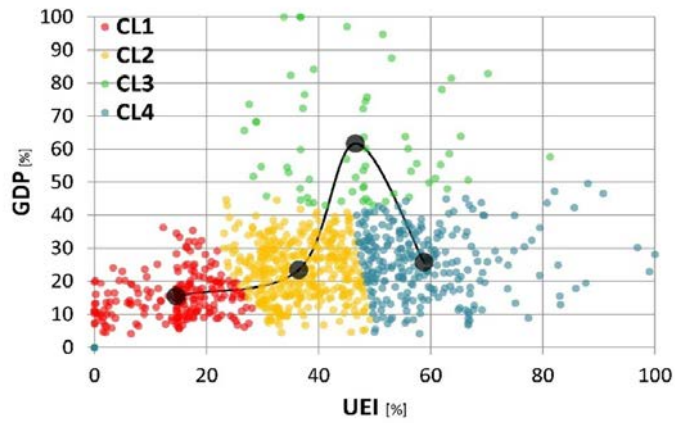
Fig. 3. Example of clustering; UEI and GDP normalized from 0 (worst) to 100 (best). According to the assumptions of the research, red corresponds to worst, yellow to middle, green to good and blue to best performances, respectively.
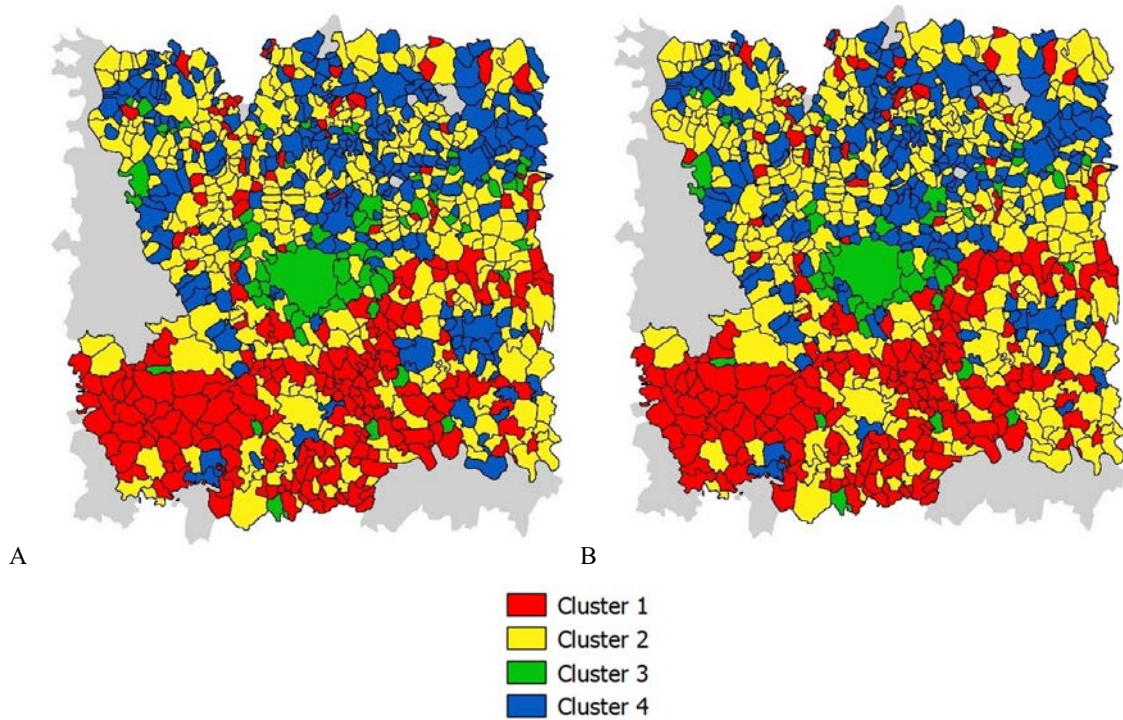

Fig. 4. Map of clustering. Results of the sensitivity analysis in relation to different definition of urban density.
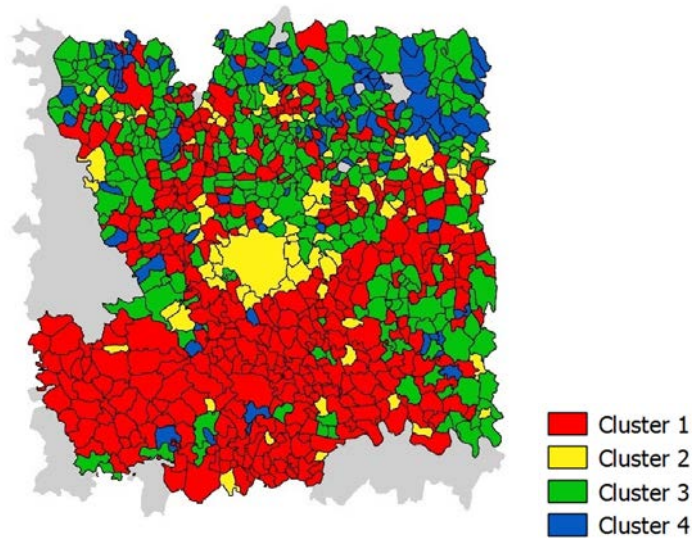
Fig. 5. Example of clustering. Results of the sensitivity analysis where the socio-economy subsystem is neglected.

4. Conclusions

In order to evaluate urban efficiency by a metabolic approach, a synthetic, transdisciplinary, transparent, customizable and human-friendly index was elaborated and tested.

The dimension of the territory, the availability of municipal data and the possibility to update and customize results represent important strengths of the research. Unlike other kind of applications, this approach permitted a geographic representation of the results. This novelty is the result of the cooperation among the multitasking and multidisciplinary working group. The clustering of results and the sensitivity analysis represent important methods for representing complex phenomena, targets and scenarios.

Due to lacks of data, the application of the model did not permit a diachronic representation but only a snapshot (dated back to year 2012) and future scenarios. Other criticalities of the model regard:

- the difficulty to grasp urban dynamics;
- the sensitivity of the results in relation to parameters, levels of importance and benchmarks (issues much debated in the working group, but not reported in the present paper);
- the need of expertise and skills in the working group;
- the need of a general agreement about the aims and the effects of the policies among the involved stakeholders.

Despite of these criticalities, this work represents an important attempt in adopting metabolic analysis as a method for supporting decision and defining policies towards more sustainable urban areas (i.e. the new administrative boundary called metropolis in Italy). The authors hope that the work can represent an important contribution in order to verify the capability of metabolic analysis to describe the functionality of a territory and to define new urban boundaries.

The overall structure of the model, the definition of the subsystems, the set of the parameters, the adopted benchmarks and the levels of importance should be better verified and calibrated as further developments, towards similar applications in other or similar contexts.

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