Towards sustainable cities. Analysis and improvement of the urban metabolism of Lugano and Barcelona

P. Caputo
Building Environment Science and Technology Department, Politecnico di Milano, IT

A. Vancheri, P. Giordano
Accademia di Architettura di Mendrisio, Università della Svizzera italiana, CH

ABSTRACT

The present work started in the framework of an academic research aimed to study urban systems and urban models taking into account the relationships among urban structure, energy consumption, emissions of pollutants and CO_2 and depletion of resources. Main aims of the work are the definition of a useful notion of urban metabolism, the implementation of a methodology for assessing it, and the application to case studies. Core of the first part of the research is the analysis of the most significant energy and mass flows characterizing urban metabolism and their representation through hierarchically organized system of variables. This representation of urban metabolism enables us to evaluate the efficiency of the metabolism of a city, the requirements to maintain the present organized urban structure or the economic, social and environmental costs needed to improve resources management or living condition. The performance of the system is evaluated splitting it in defined subsystems that are analyzed by means of a model based on fuzzy inference and through useful indicators. The "user-friendly" structure given by the application of fuzzy methods permits also the introduction of a qualitative component that can help in giving a more communicable and fitting description of the complexity of the processes related to an urban area. At this moment, data about the cities of Lugano and Barcelona have been processed for testing the prototypal model. As further development, an application of the model to a significant set of cities could permit to compare the different performances giving an assessment of the city system and of its subsystems also referring to defined benchmarks. If a significant sample of cities is processed, output given as results of the model can support policy makers, public utilities, urban designers and other stake holders in defining strategies for improving the performance of the different urban areas looking at their features, weaknesses and potentialities. Further, the modular structure of the model, permits also to easily complete and improve the model, and to analyze the singular performances of the different subsystems; this can be very useful for the individuation of the strengths and weaknesses of a city and also for redirect economical-financial efforts in the most effective way in order to improve quality of life saving natural resources and limiting environmental impacts.

1. INTRODUCTION

The wide and long-lasting debate related to the global environmental emergencies, population dynamics, energy demands trend and resources depletion was recently stressed again also in the framework of the EU 20-20-20 energy package and following targets for each EU Country member.
The importance of the role of built environment and of urban systems has been underlined again, stressing the need of a revolution in order to change the present systems and trends towards more environmentally conscious, sustainable and renewable based urban areas. Urban districts and

communities represent an optimal scale for promising strategies towards sustainability including a more efficient use of energy and fossil fuels consumption reduction, i.e. promoting local renewable energies use, distributed generation, micro-cogeneration and multi generation. Focusing on urban energy systems, it has to be stressed that, a part some particularly lucky cases, these are very obsolescent, not efficient and fossil dependent. To that end it is very important to provide reliable models and applications in order to improve energy systems limiting the risk of dangerous errors and difficultly predictable negative effects. To that end, a suitable analysis of urban systems and an innovative survey and development of urban models, aimed to deeply understand how urban metabolism can be improved, could be very appropriate and useful. In this framework, present work tries to give a contribution in defining urban metabolism and a methodology for assessing it, giving also a sample of application to a couple of cases. Data related to urban metabolism (main energy and matter flows related to built environment, mobility and other urban activities) are collected and elaborated in order to evaluate suitable indicators to be connected in a model able to represent a vision of urban metabolism and of the relative potential improvements, enlarging the evaluation to the most suitable aspects of the quality of living versus resources depletion and environmental problems. This model has been developed taking into account important researches in which, despite the enormous complexity and diversity of human behavior and extraordinary geographic variability, as a metaphor, cities were modeled as organisms belonging to the same urban system governed by defined laws (Butera and Caputo 2008).

2. CONSTRUCTION OF AN EUROPEAN URBAN EFFICIENCY INDEX

Like biological living systems, cities are characterized by massive inflows of energy and matter that sustain all the processes that make their lives possible. As a consequence of this processes, cities discard in the environment flows of matter and energy in form of pollutants, waste and heat. The efficiency is the capability of the system to be productive with a low level of dissipation. We will measure the efficiency of an urban system through a sort of cost-benefit balance that will be provided by an indicator called urban efficiency index.

In order to obtain a suitable definition of urban metabolism we will represent a city as a system made of different subsystems. From a functional point of view, a meaningful subdivision we can consider is the following:

1. Transportation subsystem;
2. Built environment subsystem;
3. Cultural, healthy, sociological and economical subsystem.

Each one of these subsystems can be abstractly represented as a machine that takes some quantities in input (usually, they are either masses or energies of some type) and produces two types of outputs (Figure 1). The first one has to be thought as “negative outputs”, e.g. every kind of waste produced by the subsystem. The other one (also called productivity of the subsystem) consists in all the quantities that are purposely produced by the subsystem as objective of its existence. In accordance with e thermodynamics analogy the productivity has to be thought as a form of useful work. We can hence state that we are thinking at a city as a network of engines producing some form of useful work (its products). These outputs are produced through exchanging of matter and energies with the external world or with other subsystems of the same city. Each one of these subsystems has its own efficiency, depending on our evaluation of its inputs and outputs. All together, these efficiencies contribute in our definition of the overall urban efficiency. The main aim of the present work is to define a suitable set of subsystems (also depending on the available data) and to define their efficiencies using fuzzy logic methods.

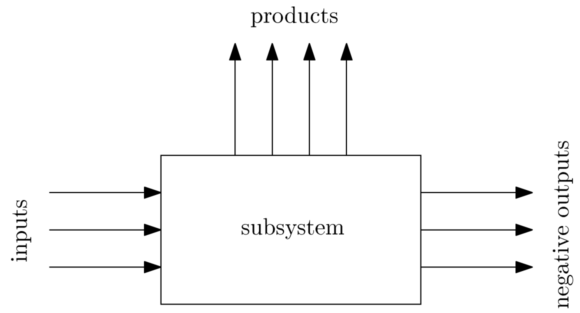

Figure 1 The general metabolic schema for subsystems.

The metabolic representation of the transportation, the built environment and the cultural-social-economical subsystems are showed in Figure 2, Figure 4 and Figure 3 (see section 3 for the meaning of the variables used in these figures). Subsystem 3 has been represented in an extremely idealized way, with neither input nor negative output. Of course, this assumption can be criticized, but the main aim of the present work is to show the methodological approach we have used for the construction of the European Urban Efficiency Index and some of its possible uses. A more complete representation, including the industrial sector, taxes and other inputs, has not been considered in this work because the corresponding data are not available for Lugano, at the date of publication of this contribution, but will be considered in future versions.
Figure 4 and Figure 3 underline the selection of parameters able to describe: energy performance; global impact (i.e. CO_2) and local impact (i.e. NO_x) of each subsystem.

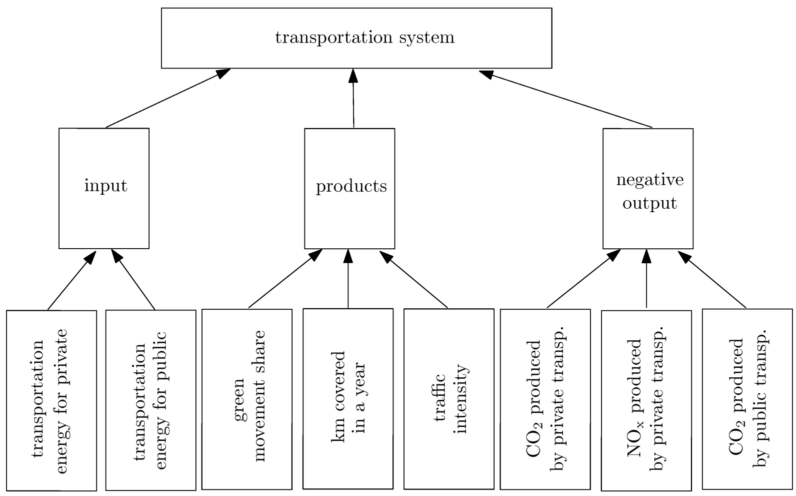

Figure 2 The I/O metabolic schema for subsystem 1

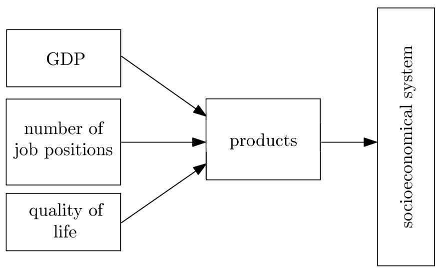

Figure 3 The I/O metabolic schema for subsystem 3

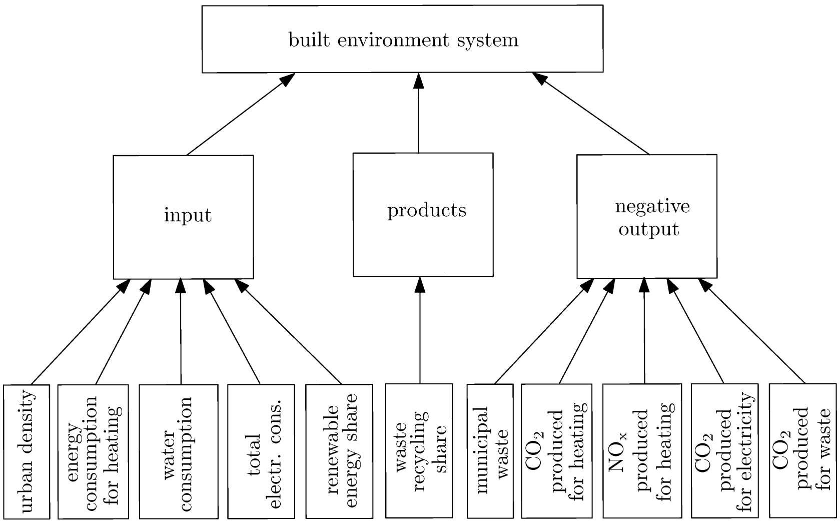

Figure 4 The I/O metabolic schema for subsystem 2

3. FUZZY EVALUATIONS

A glance to the figures Figure 2, Figure 4 and Figure 3 shows that the input-output schema of each subsystem lead to a hierarchical organization of the variables. Data are first aggregated in accordance with the input, negative-output and productivity classification. These aggregate variables are further aggregated to obtain an indicator of the efficiency of each subsystem and finally (not shown in the figures) to obtain the overall measure of the efficiency of the system.
The construction of a measure of urban efficiency requires the definition of criteria for aggregating variables at all the level of the hierarchy. We started converting the data of Table 1 in evaluations in a scale conventionally ranging from 0 to 100. These evaluations have been obtained assigning reference values to each variable corresponding to worst, medium and best cases. Evaluations equal to 10, 50 and 90 has been assigned conventionally to these reference values. The evaluation of a generic value of a variable is computed using piecewise linear functions based on the reference values and evaluations (with an "asymptotic" saturation of the evaluations for values outside the reference extremes). Details about the specific choices are exposed in the subsections 3.1, 3.2 and 3.3. The aggregation of the variables at higher and higher levels of the hierarchical structure has been obtained using fuzzy inference systems (see e.g. Siler and Buckley, 2005; a fuzzy system has been defined for each one of the block in figure Figure 2, Figure 4 and Figure 3). A fuzzy inference system can be thought as a set of models relating input to output variables. Each model is associated with a IF…THEN rule that represents the conditions on the input variables that make the corresponding model applicable: if the input variables fulfill the condition expressed by the antecedent IF, then the model associated with the consequent THEN is applied to compute the output. Fuzzy systems are different from other kind of rule-based models because the conditions expressed by the antecedent IF can be fulfilled with a degree between 0 and 1. For this reason more than one rule can be activated simultaneously (with different degrees) by the same set of input variables and, as a consequence, different models will come into play simultaneously. The output is given by a logic procedure that is suited for weighting the contributions of each model to the final result based on the level of activation of the respective rules.
Thanks to the structure exemplified by the system of rules, fuzzy inference systems are especially useful in the representation of expert's knowledge. For computing the higher level variables of the hierarchy we have first defined a level of importance of each input variable in a conventional scale from 1 to 5 and hence defined fuzzy rules. corresponding roughly to the following simple idea:

whenever the input variables have average values (that is not too small or too large), the output of the system will be given by a weighted mean (with weights given by the level of importance); the appearance of extreme values will bias the output given by the weighted mean in accordance with the importance of the anomalous variable. This rules enable us to implement evaluation criteria in which important variable are associated to necessary conditions for obtaining a high output evaluation (this effect overcame a typical problem with pure means, where good and bad evaluations tend in many cases to balance one with the other).

3.1 Transportation subsystem

The evaluations of the energy for private transportation (cars, vans and trucks), of the corresponding CO_2, and, finally, of the NO_x produced by private transportation, are all based on the km covered in a year in a urban cycle. To evaluate these km we started from best, medium and worst evaluations of the total amount of km covered in a year in every driving cycle. They have been fixed as best = 6000 km/y, medium = 12000 km/y and worst = 24000 km/y. The New European Driving Cycle (see e.g. http://en.wikipedia.org/wiki/New_European_Driving_Cycle) is supposed to represent the typical usage of a car in Europe. It consists of four repeated EVE-15 driving cycle and Extra-Urban driving cycle. In this typical usage, the Extra-Urban cycle correspond to 63% of the total covered km. For a urban driving cycle, we have hence fixed best = 2200 = 6000·37% km/y, medium = 4400 = 12000·37% km/y and worst = 8900 = 24000·37% km/y.

Energy for private transportation:

In this case, for simplifying the methods, all evaluations refer only to cars. The best evaluation corresponds to a total of 2200 km/(y·veh) (urban cycle) and an average consumption of 0.897 kWh/km (= 0.0767 (l/km)·11.7 (kWh/l)), i.e. 1.97 MWh/(y·veh) or less. The medium evaluation corresponds to a total of 4400 km/(y·veh) and an average consumption of 0.897 kWh/km of gasoline, i.e. 3.94 MWh/(y·veh). The worst evaluation corresponds to a total of 8900 km/(y·veh) and an average consumption of 0.897 kWh/km of gasoline, i.e. 7.98 MWh/(y·veh) or more.

Level of importance in the final index: 3.

Energy for public transportation:

It is not easy to evaluate the energy used for public transportation and the corresponding amount of CO_2 produced. Indeed, on one hand we would like to say that a good public transportation system uses a small amount of energy and produces less CO_2 with respect to a worse public transportation system. On the other hand, a city characterized by a poor use of the public transportation would use small energy and produce small CO_2. Our idea is to compare, e.g., the energy per passenger of the public transportation with the energy per vehicle of the private transportation. We assumed that public system will be "best" if it is able to use less than 75% of the energy used by the "best" amount of energy per private vehicle. Of course, instead of 75% we can use another percentage, expressing the convenience of the public system with respect to the private one. Analogous ideas have been used to find the "medium" and the "worst" evaluations, and to evaluate the CO_2 produced by public transportation. An estimation of the number of passengers of the public transportation system has been obtained using the green movement share, see below. For these reasons, we assumed that the best evaluation corresponds to 1.48 = 1.97·75% MWh/(y·inh) or less. The medium evaluation corresponds to 2.96 = 3.94·75% MWh/(y·inh). The worst evaluation corresponds to 5.99 = 7.98·75% MWh/(y·inh) or more. Level of importance in the final index: 3.

CO_2 produced by private transportation:

In this case, for simplifying the methods, all evaluations refer to cars. The best evaluation corresponds to a total of 2200 km/(y·veh) and an average production of 190 g/km of CO_2, i.e.

0.42 t/(y·veh) or less. The medium evaluation corresponds to a total of 4400 km/(y·veh) and an average production of 190 g/km of CO_2, i.e. 0.84 t/(y·veh). The worst evaluation corresponds to a total of 8900 km/(y·veh) and an average production of 190 g/km of CO_2, i.e. 1.69 t/(y·veh) or more. Level of importance in the final index: 4.

NO_x produced by private transportation:
Only gasoline passenger cars with direct injection engines are considered in the present work for the evaluation of nitrogen dioxides, taking into account http://www.eea.europa.eu/data-and-maps/figures/term34-estimated-share-of-pre-euro-conventional-and-euro-i-v-gasoline-and-diesel-passenger-cars-and-light-duty-vehicles-1, EU5 (2010) and http://en.wikipedia.org/wiki/European_emission_standards. Since, the best evaluation corresponds to a total of 2200 km/(y·veh) with vehicles distribution of 10% electrical and 90% Euro 5, i.e. 0.12 kg/(y·veh) or less. The medium evaluation corresponds to a total of 4400 km/(y·veh) with vehicles distribution equal to the 2008 European distribution of vehicle fleet, i.e. 0.76 kg/(y·veh).
The worst evaluation corresponds to a total of 8900 km/(y·veh) with vehicles distribution of 100% Euro 3, i.e. 1.33 kg/(y·veh) or more. Level of importance in the final index: 4. Our choice for the evaluation of the level of nitrogen dioxides produced by private transportation, can be really improved if we have data about the length of the average covered path in our city and the average speed used in this path.

CO_2 produced by public transportation:
The best evaluation corresponds to 0.32 = 0.42·75% t/(y·inh) or less. The medium evaluation corresponds to 0.63 = 0.84·75% t/(y·inh). The worst evaluation corresponds to 1.27 = 1.69·75% t/(y·inh) or more. The evaluation of the nitrogen dioxides produced by public transportation has not been considered in the present work because the corresponding data are not available.

Green movement share:
The green movement share is the average percentage of citizens using slow or public transportation with respect to all the people moving in the city (i.e. using also private transportation). The best evaluation corresponds to 50% or more. The medium evaluation corresponds to 40%. The worst evaluation corresponds to 30% or less. Level of importance in the final index: 3.

km covered in a year:
This quantity represent the average amount of km covered by a private car in a year in a urban driving cycle. The best evaluation corresponds to a total of 2200 km/(y·veh) or less. The medium evaluation corresponds to a total of 4400 km/(y·veh). The worst evaluation corresponds to a total of 8900 km/(y·veh) or more. Level of importance in the final index: 4.

Transportation intensity:
The *transportation intensity* $I_r(t)$ of a given road r is defined as the ratio between the measured flux $q_r(t)$, at a given time t, of vehicles on the road and the maximum capacity q_{max} of the road, i.e. $I_r(t):= q_r(t)/q_{max.}$ (see, e.g., Slinne et al., 2005). To obtain a fuzzy evaluation of the transportation intensity, we propose the following procedure: Let us suppose to have an estimation of the hourly average distribution of the transportation intensity for each link of the roads network (this can be obtained using suitable transportation simulation software, calibrated using a sufficient number of real flux measure points). Let us consider all the links passing the filter threshold of $I_r \geq 0.8$ for at least 1 hour per day. They can be interpreted as the most used (and hence important) roads of our network. Let $l_{0.8}$ the total length of these filtered links. Let us consider all the links passing the threshold of $I_r \geq 0.9$ for at least 1 hour per day (which, usually, is the hour of worst jamming, e.g. from 17:00 to 18:00). Of course, they will be a subset of the previous set of filtered links. This set can hence be interpreted as

the subset of jammed links among the most important link of the roads network. Finally, let $l_{0.9}$ be the total length of these jammed links.
Our evaluation is based on the fraction $l_{0.9}/l_{0.8}$. This fraction can be thought as an estimation of the probability to be, using one of the most important roads of the network, in a jammed situation. Since: The best evaluation corresponds to l0.9/l0.8 = 10%. The medium evaluation corresponds to l0.9/l0.8 = 30%. The worst evaluation corresponds to $l_{0.9}/l_{0.8} \geq 50\%$. Level of importance in the final index: 4.

3.2 Built environment subsystem

Urban density:
The urban density is defined as the ratio between the number of inhabitants and the urban surface area, which is the area of the real built surface. The best evaluation corresponds to 9600 inh/km2, i.e. the urban density of a dense and big city like Singapore. The medium evaluation corresponds to 5800 inh/km2, equal to the mean value between the best and the worst values of urban density. The worst evaluation corresponds to 2000 inh/km2, roughly indicating a high level of European urban sprawl. Level of importance in the final index: 4.

Energy consumption for heating:
The energy demand for heating takes into account for the worst and medium evaluation (set equal to 200 and 110 kWh/(m^2·y) respectively), the state of the art in Europe (referring, in particular, to residential buildings) and for the best evaluation, the Swiss Minergie standards (38 kWh/(m^2·y), see www.minergie.ch, weighted energy parameter for new multi-units residential buildings). Furthermore, efficiencies of 95% (best case), 90% (medium case) and 85% (worst case) have been taken into account as generation systems giving, at the end, energy consumptions for heating generation of 40, 122 and 235 KWh/(m^2·y) respectively.
Further, since the climate affects in a very important way the heating demand, these standards have been normalized in respect to the days of Lugano (2638 K·d), that could be taken as representative of a medium European climate. Therefore, the best evaluation corresponds to 16.80 kWh/(m2·K·d·y) or less. The medium evaluation corresponds to 46.30 kWh/(m2·K·d·y). The worst evaluation corresponds to 89.20 kWh/(m^2·K·d·y) or more. Level of importance in the final index: 5.

Water consumption for buildings:
The present version of the index has been calibrated on European cities. For non European cities the valuation of the water consumption for buildings must be changed, e.g. considering "worst" also values less than 100 liters per inhabitant per day (in these cases, drinkable water availability becomes a sanitary problem). The best evaluation corresponds to 150 l/(inh·d) or less (partial water recycling could be assumed) . The medium evaluation corresponds to 250 l/(inh·d). The worst evaluation corresponds to 300 l/(inh·d) or more. Level of importance in the final index: 3.

Total electricity consumption:
As electricity consumption, only lighting and appliances have been taken into account (without air conditioning). The values take into account the state of the art in Europe, considering as basis residential or commercial buildings equipped with high efficiency lighting and appliances and managed by an energy conscious approach. Therefore, the best evaluation corresponds to 15 kWh/(m2·y) or less. The medium evaluation corresponds to 25 kWh/(m2·y). The worst evaluation corresponds to 40 kWh/(m^2·y) or more. Level of importance in the final index: 5.

Renewable energy share (renewable electricity/total electricity):
This share has been calculated as the ratio between the amount of avoided primary energy (i.e. primary energy I would have used in case I have not renewable sources) and the total amount of non renewable primary energy. The best evaluation corresponds to 20% or more (20% is the target

defined by the EU 20-20-20 energy package for year 2020, considering all the final energy uses). The medium evaluation corresponds to 7.5%. The worst evaluation corresponds to 5% or less.
Level of importance in the final index: 5.

Waste recycling share:
The best evaluation corresponds to 45% or more. The medium evaluation corresponds to 35%. The worst evaluation corresponds to 15% or less. Level of importance in the final index: 4.

Municipal waste:
The best evaluation corresponds to 1 kg/(inh·d) or less. The medium evaluation corresponds to 1.5 kg/(inh·d). The worst evaluation corresponds to 2 kg/(inh·d) or more. Level of importance in the final index: 4.

CO_2 produced for heating:
This calculation takes into account the previously described energy consumption for heating. Despite of the very large alternatives relative to heating plants and systems, only gas fuelled plants have been evaluated, considering a mean emission factor of 200 gCO_2/kWh. Therefore, the best evaluation corresponds to 3.40 g/(m^2·K·d·y) or less. The medium evaluation corresponds to 9.30 g/(m2·K·d·y). The worst evaluation corresponds to 17.80 g/(m^2·K·d·y) or more. It has to be stressed that also these values are normalized on the basis of the degree days. Level of importance in the final index: 5.

NO_x produced for heating:
From the point of view of production of NO_x, we considered only gas fuelled systems for heating and we took one value as medium – best configuration (about 80 mg/(m^2·y) of NO_x) and another one for worst configuration (about 120 mg/(m^2·y) of NO_x). Therefore, as for the previously described CO_2 values, the best evaluation corresponds to 1 mg/(m^2·K·d·y) or less. The medium evaluation corresponds to 4 mg/(m^2·K·d·y). The worst evaluation corresponds to 11 mg/(m^2·K·d·y) or more. It has to be stressed that also these values are normalized on the basis of the degree days.

Level of importance in the final index: 5.

CO_2 produced for electricity:
This calculation takes into account the previously described electricity consumption. Despite of the very large alternatives relative to power generation in each Country, following emission factors have been taken into account for describing that wide panorama: 200 gCO_2/kWh for the best case (renewable, nuclear and partially gas based power generation), 450 gCO_2/kWh for the medium case (fossil, nuclear and renewable based power generation) and 700 gCO_2/kWh (totally fossil fuels based power generation, including a mix of gas, oil and coal) for the worst case. Combining these values with the electricity consumption values, we obtained that: The best evaluation corresponds to 3 kg/(m2·y) or less. The medium evaluation corresponds to 11.30 kg/(m2·y). The worst evaluation corresponds to 28 kg/(m^2·y) or more. Level of importance in the final index: 4.

CO_2 produced for waste:
Despite of the very large differences that can be founded in relation with the age and the performance of the incineration plant and with the characteristics of waste treated in these plants, an average emission factor of 468 gCO_2/kg treated waste has been taken. This value includes the fact that part (about the half) of waste is organic and its incineration can be considered as carbon neutral. Since, best, medium and worst evaluations depend only on the per capita amount of waste produced. Assuming 1, 1.5 and 2 kg/d per capita as waste generation, respectively, and considering about 33 m^2 per capita (mean value taken as constant in each evaluation), we obtained that the best evaluation corresponds to 5.50 kg/(m2·y) or less. The medium evaluation corresponds to 7.70 kg/(m2·y). The worst evaluation corresponds to 10.30 kg/(m^2·y) or more. Level of importance in the final index: 4.

3.3 Socioeconomic subsystem

GDP:

The GDP has been evaluated using the Siemens data set (see Siemens AG 2009). The best evaluation corresponds to the 80th percentile or more, the medium evaluation to the median, and the worst corresponds to less than the 20^{th} percentile. The best evaluation corresponds to 40000 euro/inh or more. Let us note explicitly that using this fuzzy evaluation system, outlier values like that of Lugano (due to financial activities) are evaluated "best = 100" exactly as any other value greater that 40000 euro/inh. This saturation effect permits to avoid unrealistic overestimation of the GDP. The medium evaluation corresponds to 26200 euro/inh. The worst evaluation corresponds to 19000 euro/inh or less. Level of importance in the final index: 3.

Number of job positions

The number of job positions has been evaluated in comparison with the employment rate of the EU-27 plus Switzerland. More precisely, let n_{jp} be the number of job positions, $p_{15\text{-}64}$ the city's population with an age between 15 and 64 and $E_{27+CH} = 66.11\%$ this employment rate (source Eurostat, see EUROSTAT-ER 2010). We will evaluate the quantity $\Delta = n_{jp}/p_{15\text{-}64} - E_{27+CH}$ using the following criteria: The best evaluation corresponds to $\Delta = +30\%$. The medium evaluation corresponds to $\Delta = 0$. The worst evaluation corresponds to $\Delta \leq -30\%$. This can be interpreted as how much a random citizen of our city feels better/the same/worse, from the employment point of view, than a random European person. Level of importance in the final index: 3.

Quality of life:

In the present work, the quality of life has been estimated using the Health-adjusted life expectancy at birth (HALE) in EU-27 plus Iceland, Norway and Switzerland in 2002. HALE is the average number of years that a person can expect to live in full health, and is calculated by subtracting from the life expectancy the average number of years in ill-health weighted for severity of the health problem (see EU-HEALTH 2010). Using this index as an estimation of the quality of life, we are evaluating both the sanitary system of the city and its living conditions as a contribution to illness.

The best evaluation corresponds to 80th percentile in HALE in the previously cited data set (total population): 72 years. The medium evaluation corresponds to the median value of HALE in the previously cited data set (total population): 71 years. The worst evaluation corresponds to 20th percentile in HALE in the previously cited data set (total population): 64.88 years. Level of importance in the final index: 4.

4. APPLICATION TO THE TWO CASES OF STUDY

Data provided for Lugano and Barcelona were elaborated following the previously described method. As reference year, 2008 has been considered for the almost part of the data. First draft results are the following. Electricity consumption includes also the share related to air conditioning. Unfortunately, public utilities were not able to give us an idea of this share, both for Lugano, where electricity is used for HVAC and for Barcelona where electricity is used for VAC. About power generation, the mixes provided by the public utilities have been taken into account. Energy related to domestic hot water generation and cooking have been intrinsically included into the data of energy consumption for heating. These data come from the urban utilities and were normalized in relation to the degree days (in K·d) of each location. It has to be underlined that data for heating for Barcelona refer only to residential buildings. Renewables like solar systems, that assume an important role in Barcelona, with 6116,5 kWp of PV and 65506 m^2 of solar thermal collectors have been neglected.

For giving a more usual idea of the energy performance of the two case of study, table 2 can be considered. As general consideration, it has to be underlined that results reported in table 1 and 2 are not actual overall results for Lugano and Barcelona, but they refer to the sum only of data provided and here commented.

Table 1 The data collected for Lugano and Barcelona and used for the evaluation of the European Urban Efficiency Index 2009.

	Lugano	Barcelona	unit of measure
Energy for private transportation	2.26	3.39	MWh/(y·veh)
Energy for public transportation	1.21	1.63	MWh/(y·inh)
CO_2 produced by private transportation	0.50	0.83	t/(y·veh)
NO_x produced by private transportation	2.61	5.08	kg/(y·veh)
CO_2 produced by public transportation	0.31	0.37	t/(y·inh)
Green movement share	33.63	67.00	%
km covered in a year	2465.58	3476.16	km/(y·veh)
Transportation intensity	55.76	30.00	%
Urban density	3467.32	18278.88	inh/km^2
Energy consumption for heating	39.44	34.16	kWh/(m^2·K·d·y)
Water consumption	319.08	169.89	l/(inh·d)
Total electricity consumption	45.10	60.55	kWh/(m^2·y)
Renewable energy share	13.80	9.10	%
Waste recycling share	39.45	33.60	%
Municipal waste	1.47	1.46	kg/(inh·d)
CO_2 produced for heating	9.67	6.83	g/(m^2·K·d·y)
NO_x produced for heating	0.43	5.80	mg/(m^2·K·d·y)
CO_2 produced for electricity	16.96	8.66	kg/(m^2·y)
CO_2 produced for waste	0.97	3.26	kg/(m^2·y)
GDP	65260.62	47775.00	euro/inh
Number of job positions	49.78	58.75	%
Quality of life	73.02	72.06	y

Table 2 performances of Lugano and Barcelona, considering the sum of the three subsystems

	Lugano	Barcelona	unit of measure
Total non renewable primary energy	26.0	16.2	MWh/(y·inh)
Total CO_2 emissions	4.8	2.3	tCO_2/(y·inh)

5. VALIDATION OF THE INDICATOR OF URBAN EFFICIENCY

The indicator of urban efficiency defined in the previous sections is not a simple function of some measurable quantities but a complex construction connecting together many different aspects of the urban system. Thus the problem arises about how to assess the validity of the model. The use of fuzzy logic is especially suited for validation processes based on the comparison between the results provided by the indicator and the point of view of experts. Figure 5 and 6 show examples of possible questions that could be submitted to experts in this work of validation. Figure 5 represents the contour lines of the indicator of urban efficiency when two variables, the total energy consumption and the renewable energy share, are varied whilst all the other kept constant. Scenarios in which the variables moves along a contour line are classified as neutral by the indicator from the point of view of urban efficiency. Thus the shape of the contour lines in Figure 5 represents an answer to the question about the extent at which an increasing of the consumption of electric energy can be balanced by an increasing of the share of renewable energies. Figure 6 shows the change of the indicator of urban efficiency when only one of the variables is changed. The figure shows that the sensitivity of the urban efficiency to change in a variable is different in different regimes of the urban system. The existence of neutral changes of the urban configuration and of different regimes of sensitivity of variables can be compared with the opinion of experts.

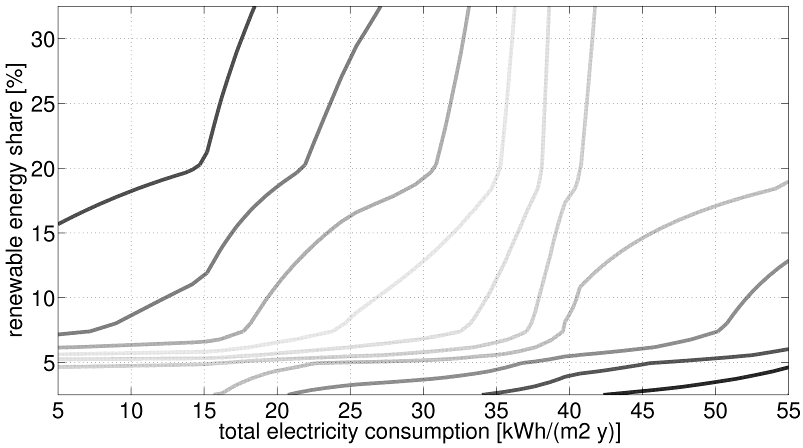

Figure 5 Contour lines of the indicator of urban efficiency. The total energy consumption and the renewable energy share are varied whilst the other variable are kept constant. The resulting section of the input space contains the configuration of Barcelona.

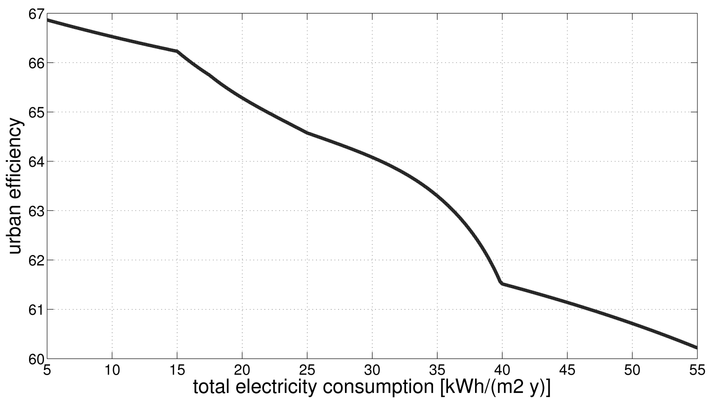

Figure 6 Variation of the indicator of urban efficiency along a fiber passing through the configuration of Barcelona.

6. PRELIMINARY RESULTS

As mentioned before, the indicator of urban efficiency defined in this paper has been computed for the urban configuration of two cities: Lugano and Barcelona. The values of the overall urban efficiency and of all the higher level indicators in figure Figure 2, Figure 4 and Figure 3 are reported in Table 3. These results are preliminary, because the indicator has not been validated in a systematic way using the approach exposed in section 5. Nevertheless the results shows how it is possible to

exploit the whole information provided by the computation of the indicator to obtain a detailed picture of the metabolic features of a city.
Figure 7 show a representations of the values of the indicator of urban efficiency trough two dimensional sections passing respectively through Lugano and Barcelona. The graphs shows similar qualitative behavior but important quantitative differences (for instance the effect of a change of the two variables is in average more important in the section of the space containing Barcelona than in the one containing Lugano). The maps can be interpreted as a representation of the potential effect of a policy that acts only on the considered couple of variables.

Table 3 indicators of efficiency of Lugano and Barcelona. The table reports the rounded values, in a scale between 0 and 100, of the indicators of urban efficiency showed in figures Figure 2, Figure 4 and Figure 3. The last rows refers to the overall evaluation of urban efficiency.

Indicator	Lugano	Barcelona
Transportation system: input	88	74
Transportation system: output	47	32
Transportation system: productivity	31	70
Transportation system: efficiency	52	57
Built environment: input	24	32
Built environment: output	70	65
Built environment: productivity	68	47
Built environment: efficiency	53	48
Socioeconomical system: productivity	99	95
Socioeconomical system: efficiency	99	95
Urban efficiency	**75**	**72**

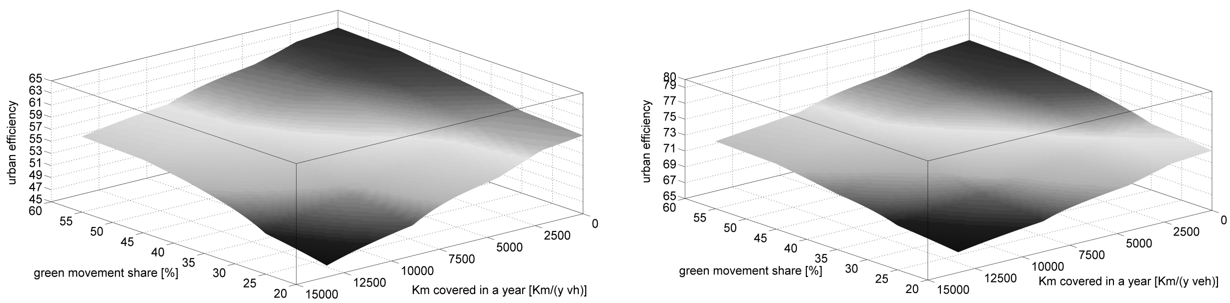

Figure 7 variation of the indicator of urban efficiency along a section of the input space containing Lugano and Barcelona. The share of green movement and the amount of km covered in a year are varied whilst the other variable are kept constant.

7. CONCLUSIONS

Urban evolution is probably the main topic and problem to face today and the same will be in the next future. The modelling of urban systems and relative changes is an activity that involves many research groups at international level.
This part of USUM work represent the first step towards the definition of a computational urban model in which resources (money, energy and matter) availability, consumption and management have been linked to the consequent improvement (or not) of comfort condition and quality of living in urban areas. These two big faces have then put in common in order to evaluate an urban

efficiency. To that end, the analysis has been split to different subsystems (layers) that can be also interconnected (simulating, in this way, more complex relationships, feedbacks etc).
In this process we met many difficulties, mainly related to define urban metabolism and urban efficiency, to get suitable and reliable data for our evaluations and to develop a procedure able to support people that could be involved in decisions related to urban changes.
In particular, through this experience we realized that a lot of efforts are needed in collecting data for a whole city, especially for energy parameters and more especially for cooling. This action could be successful only if the public utilities involved in energy supply and management are known and ready to extract the data.
Further, we are conscious that we worked only on two cities at this moment. First, these two cases are very different basically for their different dimensions, climate and living conditions and people behaviour, so, any comparison aimed to select the best of the two, from any point of view, take not sense. Second, these two cases cannot represent the wide and complex urban world, neither the European one. To that end, other cases and evaluations are needed.
Furthermore, we learned that the change from economy towards finance is a process that involves many areas; for example, the liberalization of the electric market push energy company in managing electric supply and distribution maximizing their profit and using also renewable share in the most effective way. As results, when we define our reference power mix in our calculations, we have to take into account also this kind of energy exchanges at regional, national and international level. This approach could bring results not exactly expectable following the common opinion. And these considerations can affect very much decisions about new renewable based energy paradigma, for example.
Despite of these considerations, we think that after managing a significant sample of cases of study, the capabilities of our models could help in representing results; for example, clustering cities on the basis of selected parameters could help in defining group of cities with analogous characteristics or performances and in comparing the different groups (i.e. energy consumption in relation to urban density, or renewable energies percentage in relation to GDP, or services accessibility in relation to urban population etc). From the comparison and taking into account actual policies, economic and technological conditions, it is possible also to define different scenarios for improving the metabolism of a city in the future or, on the other hand, for accounting combinations of actions whose effects permit to conserve the present performance (in other words, how have we to reallocate our resources in order to perform defined changes without further economic or environmental or social costs?).
As conclusion, we know very well that it is very difficult to develop a model able to take into account urban complexity and urban people behaviour, but we hope that the simplified, transparent and human-friendly model here presented could be useful to that end ones it will be fully tested and calibrated. In fact, as mentioned before, future developments will be aimed to test the model with other cases of study and to compare results obtained by other kind of tools and methodologies.

8. AKNOLEDGEMENTS

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