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TRANSFORMATION OF AN URBAN COMPLEX SYSTEM INTO A MORE SUSTAINABLE FORM VIA INTEGRATED MODIFICATION METHODOLOGY (IMM)

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ABSTRACT

Cities are energy-using systems in their own right; they consume energy in varying levels of efficiency. A city's form can have a tremendous effect on its energy consumption, as well as its environmental performance. There has been much research and discussion regarding which urban form is sustainable, but lack of constructive methods to improve upon their existing environmental performance. This paper explicates a possible method of sustainable urban transformation design principles. The methodology aims to reform an existing urban assessment into a more sustainable form, regardless to its present form and performance. The research demonstrates how one can transform a city into a lower energy consumption system, using the Integrated Modification Methodology. In this approach, the city is considered as a single entity, a Complex Adaptive System; accordingly, the sustainable urban form emerges through modification of its elements and integration of its subsystems over time.
Keywords: complex adaptive system, integrated modification methodology, morphology, sustainable urban transformation

GLOSSARY

Analysis/investigation phase:
The phase in which the designer dismantles the complex system into its first-level subsystems in order to observe their individual characteristics and their configurations.

Bond:
A specific way of interrelating the components of the system; the architecture of the bonds affects the structure of the system.

Catalyst:
The catalyst is the layer that starts the reaction of the system. It drives the local transformation, thus activating the transformation of the system. The choice of the catalyst depends on the investigation phase.

Complex adaptive system (CAS):
CAS is a specific type of the complex system (CS) with adaptive and resilience ability. The final performance of the CS is different than the sum of its heterogeneous elements' performance.

Complexity:
In the IMM process, complexity belongs to SLS. It is a typological aspect, which explains diversity and mixture of the CAS.

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Compactness:
In the IMM process, compactness belongs to SLS. It is a morphological aspect that explains how dense or diffuse a city is, and how near or far different functions are with respect to each other; thus, the compactness is the integration of proximity and porosity, the second level of integration of volume, void and function layers.

Constituents:
Constituents are interrelated components, represented as a single element or a subsystem, which through their connections with other components provide a certain physical arrangement of the CAS.

Connectivity:
In the IMM process, connectivity is a technological aspect belonging to the SLS. Connectivity describes the transportation of physical objects, as well as data and information exchange.

Design/transformation phase:
The phase that drives a structural change in the physical arrangement of the CS and results in a discrete transition of the system into another state.

Design operator principle (DOP):
DOP are tools/instruments used to arrange the structure of the CAS. The application of these principles affects CAS structure and its performance. DOPs are associated with indicators.

Evaluation/comparison:
Appraisal of the IMM process, through the comparison of the system's performance, before and after the intervention

First level of superimposition (FLS):
Superimposition of the principle (inner) layers.

Hypothesis/assumption and interpretation phase:
The phase that comes after the analysis of the system. At this stage, the selection of the catalyser (Hypothesis phase) anticipates the startup of the modification process (Design Phase).

Horizontal investigation:
Preliminary disassembly process of the CAS components. Analyses of physical assessment of the subsystems (layers), which affect the urban morphology: volume layer; void layer; functional layer and transportation layer.

Horizontal modification (HM)/horizontal adaptation:
The HM starts the reaction of the system. This local (Horizontal) modification of the existing layers, in particular the catalyst, activates the transformation of the CAS.

Key categories (KC):
KCs are morphological, typological and technological features – determinatives – expressed by the superimposition, or symbiotic integration, of CAS subsystems (inner layers). KCs are applied in the

investigation phase for analysing the urban context and its performance before the design intervention, as well as in the final as evaluation phase after the intervention. Here, the key categories are: porosity, proximity, diversity, interface, accessibility and efficiency.

Integrated modification methodology (IMM):
A process that improves the complex adaptive systems' performance, based on modification of its constituents.

Indicators:
A core set of elements based specifically on environmental themes but interlinked with other themes social, i.e. economy. They are used in the IMM process for comparing the characteristic performance of the system, prior to and after the transformation design process.

Layer:
The CAS comprised superimposition of an enormous number of layers or 'subsystems', such as social, political and economic layers, which are distinguished into:

- Primary layers: The main layers of sustainability; this may include the Social layer, the Economy layer and the Environmental layer.
- Inner layers: subsystems which create the Primary layers. In this research, the authors focus on the inner layers related to the physical arrangement of the city and total energy consumption of the city: Volume, Void, Function and Transportation layer

Links:
A way in which two constituents of a system are connected or related. The Horizontal (local) connections inside the same layer and the Vertical (global) connections between different layers are both important for explaining the CAS' assessment (organization).

Multi-layers:
The involvement of different layers in the CAS; here, in the framework of IMM multi-layers could refer to the involvement of different expertise in different disciplines.

Multi-scale:
Covering all scales of interventions without sequential order. An approach to complex physical systems that have important features at multiple scales, particularly multiple spatial and/or temporal scales. These cross-scale effects are of great significance in the dynamics of CASs. At any particular scale, the system is actually a sub-system. Multi-scale approach is needed to understand the behaviour of the complex systems.

- Global scale: Global scale interaction emerged through nonlinear local interactions of the constituents.
- Intermediate scale: The bridge between local scale and global scale; it plays a vital role to change the global scale transformation through the local scale modifications.
- Local scale: Local scale interactions of the constituents influence large-scale behavior and arrangement.

Reactant/reagent:
A reactant is a starting material of the system (subsystem), less specifically, a 'Layer' that is modified in the course of a reaction/transformation process activated by the catalyst.

Second level of superimposition (SLS):
The results of the symbiotic integration of the key categories, i.e. superimposition of the inner layers.

Subsystems:
The members of a CAS which either share the same function or directly relate to each other are categorized in a subsystem. The subsystems are often a complex adaptive system on their own. They work depending on the condition such as catalyst or reactants. The principal investigated subsystems, are as follows: volumes; voids; function and transportation.

Superimposition:
Due to the fact that the CAS is composed of four or more subsystems, it is considered to be a superposition of products of the subsystems' states. Superimposition is a process of integration of two or more sub-systems. Once the subsystems interact, their states are no longer independent.

Transformation:
The conversion of a system's configuration and performances, through several adaptation processes, in order to fulfill the new system's demands and response to new imposed constraints.

Vertical investigation:
Preliminary evaluation of the actual performance of the CAS (urban context at present state) before the design intervention, by utilizing selected KCs.

Vertical modification (VM)/vertical adaptation:
The VM or vertical adaptation occurs between the different subsystems and is a reaction of the system as propelled by the project. The VM is driven by the response of the reactants' layers catalysed by a selected layer (catalyst), which also modifies the architecture of the ligands between the subsystem.

Volume and void
Volume refers to the amount of built-up spaces in the urban fabric, when void refers to open spaces.

1 PRELUDE

Over half of the greenhouse gas emissions are created in and by cities; the majority of the population lives and works in cities, where up to 80% of energy is consumed [1]. Thus, urban design principles can address the challenges in a tolerable way, facilitating the conciliation between development and sustainability.

The onward march of the population's growth rate is reaching a dramatic measure and has created a series of questions regarding the overall ecosystem's sustainability. As a matter of fact, this unrestrained trend, which will lead the actual world population to 9.2 billion by 2050, and to 13.2 billion people by 2080, is an urban succession, that will have an impact directly or indirectly on other phenomena [2], such as:

- The planet's deforestation, which is related also to a progressive expansion of the land occupation for agricultural purposes.
- The unstoppable urbanization processes also associated with the new migration flows, and related to some phenomena of urban sprawling and new land occupation for housing purposes.
- The increasing emissions into the atmosphere and the steady deterioration of the quality of the air, land and water occurring in many regions of the world.

In this scenario, it is clear how urban areas, as well as their urban design, play a key role in the definition of a long-term strategy for a sustainable development, despite other ephemeral remedies. Reconsidering the location where cities should be located and designed could reduce the CO_2 emissions and energy demand, accordingly. In fact, the ultimate goal of our research is to identify useful principles and tools, aiming to direct the increasing world urbanization towards more sustainable long-term models, which are characterized by better energy performance and, consequently, better balance that would be achieved between the available resources and the required consumption [3].

Much research has been carried out regarding sustainable buildings and the energy performance of single edifices; however, there are few studies that have come out with consideration of the cities as a single unit. Moreover, a systematic methodology, that assists design planners, has not been introduced yet.

This theory considers the city as a complex adaptive system. Furthermore, it sketches out the relationships between urban morphology and energy consumption, providing some new basic design principles to re-shape urban assessment, as well as designing new sustainable neighbourhoods as an integrated part of the city.

Morphology plays an essential role for any energy-saving policy, urban efficiency, liveability and, generally, sustainable urban environments to succeed. It is necessary to adopt new principles and new urban design methodologies. One of the main objectives of the research is to find, thanks to a holistic and multidisciplinary approach, new methodologies that can help to shape a better comprehension of the different performances of different urban assessment; then, to apply to the new design principles in order to improve the system's performance.

A complex system, to put it in a nutshell, is an arrangement of interconnected heterogeneous elements that, as a whole, shows one or more performances, and the final result of the whole system is utterly different from every individual constituent's performance.

The *Complex Adaptive System (CAS)* is a particular case of the complex system with the ability to learn from prior experiences. System's agents adapt themselves to improve their performance, in response to new internal and external constraints.

The system comprised heterogeneous elements with several functions that should be classified in different ways. The members who both share the same function or a specific one are directly related to each other and categorized in a subsystem [1]. The subsystems are often a complex adaptive system in their own right (like the nervous system of the human body).

Due to the presence of different types of agents and different nonlinear relations between them, the complex systems also need many different subsystems in order to link these agents. These subsystems and networks, such as transportation, social and economical networks, make cities alive. As mentioned before, the *constituents* categorized in a 'subsystem' hereafter will be called 'layers' in the research.

According to the holistic approach, the city, considered as a *CAS*, is not solely a mere aggregation of disconnected energy consumers, and the total energy consumption of the city is different from the sum of all of the buildings consumption. This considerable gap between the total energy consumption of the city and the sum of all consumers is concealed from the urban morphology and urban form of the city.

Now that the time for debate about whether urban *compactness* or sprawl is more sustainable may be over, this discussion could be valid again, especially in the case where one wants to design a new city from zero. However, cities are not a blank white paper, so the urban design and transformation are a challenge with existing contexts and designers must deal with their transformation. The main strategy comes from the notion of the belonging, which considers the past in order to develop the future. The main concern of this research is to improve an urban system performance, regardless of its morphology. Trying to find a single sustainable pattern for urban development is not the correct way to deal with the energy sustainability problem. Being prejudiced against either the urban sprawl theory and the *compactness* pattern will not lead to the main goal, which consists of improving the urban system performance regardless of its compact or sprawl form.

The authors attempted accordingly to introduce a new design method, which is called the Integrated Modification Methodology (IMM), so as to improve the performance of the city system as a single entity. The IMM simulation methodology, based on a series of *CAS* analyses, explicates a way to propel the urban transformation to the sustainable urban form. One can utilize this integrative methodology, based on modification and integration of existing elements, to propel the gradual transformation's process towards a more sustainable direction. The main simulation lies on the premise of symbiotic relationship between members and subsystems, inside the *CAS*. According to this methodology, the energy efficiency of every element has to be optimized by its form; additionally, this element has to be designed in such a way that it improves the energetic performance of the other elements as well. The urban transformation emerges through the modification of its *constituents* and integration of its subsystems over time.

2 MODIFICATION AND URBAN COMPLEX ADAPTIVE SYSTEM

Aldo Rossi [4] and Frey Hildebrand [5] believe that city's form, and its morphology, are derived from their constituent form and physical assessment. The structure and the form of the city are the gradual emergence of the whole constituent's configuration. Any physical part of the city has a form, and the orchestration of such parts generates a specific urban form and structure.

Complexity is thus linked to a certain mixture of order and disorder, an intimate mixture that in urban systems may be partly analysed using the concept of diversity. Living organisms, and especially man and his organizations, are information carriers that dynamically in time accumulate characteristics that indicate the degree of accumulation of information and the capacity to have a significant influence on the present and to control the future [6].

In other words, the adaptation ability is flexible versus rigid, active versus passive and dynamic versus static. The cities become resilient due to this feature; henceforth, their resilient and versatile characteristics will be the main key to fulfill the new demands on sustainability urgency.

2.1 Modification

The importance of the keyword, 'Modification', has been clearly expressed by Vittorio Gregotti: 'No doubt there is no architecture without some modification of what already existed' [7]. The urban resiliency is derived from the urban dynamism, through continuous modifications and persistence of the city elements, in order to fulfill the new demands and conditions imposed on the system. 'The principle of resilience means that cities are not passive victims, but have to show flexibility by adjusting their sustainability policies to challenges and opportunities. Consequently, they have to identify, explore and select choice options which – despite their complex and conflicting multidimensionality – ensure a balanced development under changing external conditions' [8].

The fundamental notion of the morphological resilience derives from the stability of physical systems, which can be stable if minor perturbations reinforce them rather than destroy them. 'Dynamically stable urban states are those that display an enormous number of geometric and functional connections on different scales. When some connections are cut, others are created. These connective forces act on urban morphology to generate unique cities every time and transform them following singular trajectories' [9].

The modification should not be seen solely as a tactic in the design process; the designers have to foster the 'Modification' as the main design strategy and platform [10].

2.2 Chaos threshold and theory of catastrophe

The alteration in any individual agent does not influence the final performance of the system directly, whereas the system performs by integration of all of the *constituents* as a whole; conversely, a minor change could change the course of the entire system utterly. This paradoxical behaviour is one of the characteristics of the *CAS*. This behavior has been described under the Theory of Catastrophe, classified under the framework of Bifurcation. According to this theory, a sudden shift, even the slightest, could arise considerable changes in the transformation of the entire system [11]. The chaos and catastrophe features make the system unpredictable, because the relationship between cause and effect in the complex system is not smooth and linear. Complexity does not solely include quantities of units and interactions but also uncertainties in determinations and random phenomena. In a sense, complexity is always related to chance [6]. It has been illustrated that the level of uncertainty and chance is directly correlated with the number of elements as well as their complicated assessment and relation.

In order to discuss complex adaptive systems, one should first define simple linear systems by way of contrast. 'In linear systems the relationship between cause and effect is smooth and proportionate. Linear systems respond to big changes in a big and proportionate manner and linear systems respond to small changes in an equally small and proportionate way' [12]. Most of real life situations, on the other hand, are complex. Small changes in initial conditions, and later interventions of whatever size, can produce disproportionately large effects.

The chaotic behaviour of the *CAS* creates an inchoate state from which that city starts its transformation. Amorphous zones do not exist in a city, or if they do, they are moments of a transformational process, and represent a suspension within the urban dynamic. These transformations are realized through the definition of a precise area, and this marks the start of the redevelopment's process [4].

Those are the basis for an empirical study of the city as it has evolved from the consciousness and memory. During the construction's process, its original themes persist, but at the same time, it sharpens and renders these themes by its own development, more and more specifically.

2.3 Time and transformation

As mentioned prior, a dynamic system constantly changes its behavior when facing the new conditions; this behavioral alteration occurs indeed alongside the course of the time. The difference between kinematics and dynamics is their aim and goal. The kinematic approach aims at parameterizing the form or state of the process, whereas the dynamic approach attempts to illustrate the evolution and transformation of the system over the time [13].

The time is an irreversible factor in the *CAS* transformation; due to this fact, urban form never goes back to its initial form after crossing the stability's threshold. According to the Catastrophe theory, once the *CAS* reaches the stability threshold and crosses the catastrophe point, it will not be able to return to its original state and form.

One test of a *CAS* is time asymmetry. Asymmetry in time occurs when a system passes a bifurcation point, a pivotal or decisional point where an option is taken over another or others, leading to the irreversibility of the time.

Complex adaptive systems are asymmetric in time, irreversible and nondeterministic. So, in a *CAS* one can neither predict nor explain later, even with all the infinite information on the initial conditions, because the system 'chooses' its own path. Its 'choice' is indeterminate, a function of statistical probability rather than certainty [12].

The urban context form, at the unstable moment, is the base for the next morphological transformation. In the other words, the modification of the urban context is a restless process; consequently, the current state of urban context will be the base for the future transformation. It could be simplified if one refers to Aldo Rossi's quotation about different context in different states: 'the urban development has a temporal dimension, the city has a before and an after' [4].

2.4 The image of form

As a result, there are two main players, which competitively change during the transformation: the elements and the context. The rapid growth of either of them, without being chased by the other, leads to pathological transformation problems. To demystify this concept, the nonhomogeneous transformation pace of different elements of the *CAS*, particularly the elements and the context, will be concluded to mislay the system's memory. As a result of the system amnesia, the city identity will be dissipated; moreover, the image of the city will fade. The image of the city then will be achromatized by rapid and nonhomogeneous urbanization growth, leading the same cities towards the acquisition of a ubiquitous globalized image, by omitting the contextual memory.

3 INTEGRATED MODIFICATION METHODOLOGY

As mentioned above, the IMM is a design methodology with the aim to improve the performance of the *CAS*; the main characteristics of the IMM are based on three fundamental approaches: holistic, multi-layer and multi-scale.

3.1 Holistic

Due to the fact that the final performance of the every *CAS* emerges from actions of heterogeneous elements, the final behavior of the system is difficult to be anticipated. Accordingly, if one wants to deal with a *CAS*, both performance prediction and performance optimization should deal with its complexity in a holistic way. Dealing with *complexity* prompts one to face with convoluted difficulties; however, any approach based on simplification will cause unrealistic results. Dealing with complex system based on simplification can be resembled to the eight blind monks who were examining an elephant; each monk interpreted a different result based on their input parameters.

As a result, *CAS* 'refers to a field of study and resultant conceptual framework for natural and artificial systems that defy reductionist (top-down) investigation. Such systems are generally interactions result is in nonlinear complex dynamics, whose results are emergent system phenomena' [14].

3.2 Multi-layer

The multi-layer, in IMM, could be achieved via involvement of different experts in different disciplines. To reiterate, in terms of sustainability for instance, the environmental layer integration has to be implemented with the social layer, as well as the economical layer. As mentioned, in the urban field, the complex system must be studied with inclusion of its adaptive complexity if more accurate results are to be obtained; hence, the simulation of a complex adaptive system is far preferable to the simplification of the complex adaptive system in further researches.

The reason behind multi-disciplinary intervention is that any urban development plan in every field will eventually manifest itself in physical results, a product, which needs to be shaped, designed [5]. Accordingly, the neighborhood design task is not simply the urban designer duty; however, urban designers have to articulate different disciplines to achieve a uniform sustainable product.

3.3 Multi-scale

The modification of elements of the *CAS*, which causes the final transformation of the system, occurs in different scales. Equally, the urban interventions operate on different scales. As the modifications of *CAS* are classified in the minor (local), medium (intermediate) and major (global) scale, any intervention effect has to be considered in the three mentioned scales. The intermediate interventions bridge the gap between minor and major scales. In a nutshell, 'thinking global and acting local' is the main strategy.

The designers should concentrate their concern on the fixed operational area, as the medium scale, if they want to deal with minor (local) scale modification and the major (global) transformation. As Aldo Rossi mentioned regarding the urban transformation interventions, one should operate on a limited part of the city, although this does not preclude an abstract plan of the city's development and the possibility of an altogether different point of view [4].

For instance, if the city, including precinct and district levels is considered as the major scale, then the medium scale would be the neighbourhood scale and the local scale is a single building block.

The major scale: The author underlines again on the main aim of urban intervention's scale classification, which is just an explanatory method. The intervention scale approach is hierarchically independent. Although the transformation of major scale emerges from local scale modification, the major scale plans the main modification path.

The medium (intermediate) scale: The importance of the intermediate scale intervention in the *CAS* transformation has been depicted. Accordingly, in the IMM process, the designer and the planner have to specify the intermediate scale as a fixed area of intervention. The form of this specific area has to be analysed as part of the whole city. In other words, designers and planners have to specify the neighbourhood's border as their intervention area. The map the border of neighbourhood is not a simple task due to involvement of the different players, such as social, morphological and economical factors; nevertheless, in this research, the morphological parameters are the main tools to map the neighbourhood's border. The observing urban form through the formal analyses of a neighbourhood, as a constituent of the whole city, is a correct way to study the urban form.

Despite the fixed area considered as the intervention area, in the analysing process, the area has to be seen as a part of a single entity. 'In the present context, the study area always involves a notion of the unity both of the urban whole as it has emerged through a process of diverse growth and differentiation, and of those individual areas or parts of the city that have acquired their own characteristics' [4].

Accordingly, neighbourhood's border could be mapped on the base of walkable distance between the different borders. In this approach, an approximate pre-determined distance between the site's borders is considered. Following this idea, about 600-m distance between the edge of a neighbourhood and its central area and transport node seems to be a generally accepted measure.

4 FIRST LEVEL OF SUPERIMPOSITION

As mentioned before, the *constituents* of the *CAS* adapt themselves to react to the newly imposed constraints, in order to improve upon the entire system's performance. The complex adaptive system is composed of heterogeneous elements, linked together either directly or indirectly, and the final system performance emerges from all of the elements as a whole. This adaptation occurs within or on members of a single subsystem, hereafter known as *horizontal adaptation*, and between the different subsystems, hereafter termed *vertical adaptation*.

In other words, the adaptation of existing members in a subsystem, or horizontal adaptation, as a response to the newly imposed conditions and constraints, changes the subsystem's performance, which will be the cause of the entire system's transformation over time [1].

The vertical adaptation is a specific kind of adaptation, likewise where the members modify themselves to optimize the performance of the entire complex system. However, unlike the horizontal one, which occurs inside each individual subsystem, the vertical adaptation takes place between different subsystems. In other words, the subsystems interact symbiotically in order to improve their own performances, and thereby the entire system's performance level. The horizontal adaptation occurs within or on members of a subsystem (horizontal adaptation), hereafter known as 'modification', and between the different subsystems (Vertical adaptation), hereafter termed 'integration'.

One can sharpen the performances of the entire complex system, utilizing the adaptive behaviours of the *CAS*, both horizontal and vertical. The entire complex system will be transformed by the mentioned symbiotic adaptive behaviours between the elements and subsystems, modification and integration, over time. By boosting the performance of one subsystem through the assistance of the transformation of another subsystem, one creates a collaborative relation, which ultimately leads to transformation of the complex system in an optimal way. To reiterate, modification happens when the members of one layer are optimized, in order to improve their own layer's performances. On the other hand, integration is a symbiotic relation between different layers, for better performance, which ultimately improves the entire system's performance [15]. These adaptive features are the key elements of the *CAS* simulation method.

The city comprised several superimposed layers; so as to deal with urban sustainability, it means first to work on the primary layers: environmental, social, and economic layers.

Environmental layer: This primary layer refers to the demand, production and distribution of the total energy consumption of the cities in different sectors, such as transportation, domestic use, etc. It focuses on the reduction of energy demands and it cuts down on the waste. Simultaneously, it is necessary to increase the possibilities of meeting the demand using either renewal energies or sources that cause fewer greenhouse gas emissions, and making sure that they are efficiently distributed throughout the urban fabric [9].

Economical layer: The economical layer, alike the other primary layers of the city's *CAS*, is the result of convoluted action, which depends on various factors in different scales from local to global. The interest of the research is focused on local urban design and district design in particular; this covers the variety of interactions between resources, people, jobs, and shops as necessary to sustain a strong local economy. 'Sustainable cities have to support a great number and variety of resilient companies, along with job opportunities and profiles that meet the needs of the population in number, diversity and location' [9].

Social layer: The sustainability of the urban system is meaningless without the social layer. It refers to the fair distribution of the resources, qualitative and quantitative, to fulfill the whole demand. The social layer has a great impact on sustainability and urban morphology. For sure, 'the urban morphology is a cultural fact' [9].

The IMM method could be applied in different disciplines, by different experts, in order to improve the performance of a complex system. The experts solely need to choose the apt involved layers within the numerous layers of the system. It is clear that involving more layers brings more complexity and accurate result to the final modification process; however, it also makes the simulation process more complicated.

As the main interest of this research is the urban form and the energy consumption of the city, the authors tried to indicate a number of subsystems (inner layers), which are correlated with the environmental layer (primary layer) and urban form concerns. After studying the city and its main constituents, the investigated subsystems in this research, which affect the urban morphology as well as the balance of total energy of the city, have been selected as follows [1]:

- Urban *volume* (built-up mass layer).
- Urban *voids* (open spaces, streets, etc.).
- Functional layer (land use layer).
- Transportation layer.

The *first level of superimposition* (FLS), or symbiotic integration, of layers creates some morphological, typological and technological features—determinatives of the city, which are called '*key categories*' (KCs), in the sustainable urban design intervention; therefore, they could be used by designers, in the observation phase of the design process, to analyse the urban context on the actual situation and its performance before intervening (Table 1). Thanks to the results of the research carried out by the authors and based on theory plus practice, the KCs have been literally defined. In addition, some measurable *indicators* that correlated with every KC are needed to give their numerical dimensions. The KCs are fixed independently from the context, whereas the *indicators* vary. The *indicators*' definitions should be chosen differently in every specific urban context by designers and planners; the selection criteria lie precisely on the contextual constraints, conditions, intervention's intentions and available data banks [15]. According to Hildebrand, designers should pay attention to the fact that cities are all

Table 1: Superimposition of the layers; the first level of superimposition (FLS) creates the measurable *key categories*; additionally, the second level of superimposition (SLS) defines morphological, typological and technological features of the city. The city could be transformed towards a more energy efficient form, if one creates a symbiotic relation between the *key categories*.

Layers' superimposition	FLS (key categories)	SLS	Determinants	
Volume/void	Porosity	Compactness	Morphology	Energy efficient form
Volume/function	Proximity			
Function/void	Diversity	Complexity	Typology	
Transportation/void	Interface			
Transportation/function	Accessibility	Connectivity	Technology	
Transportation/volume	Efficiency			

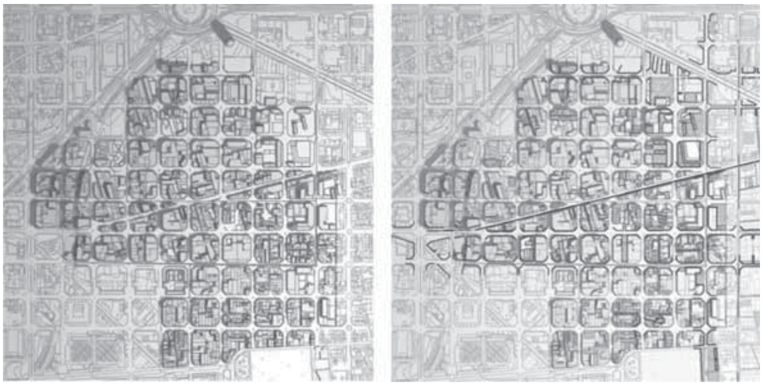

Figure 1: (Left) Porosity map: porosity is the integration of the volume and the void layer; (right) Proximity map: it shows the vicinity of the key functions to the neighborhood's dwellings.

different in form and structure, owing to a host of place-specific factors such as topography, climate and socio-economic conditions. It cannot be expected that they should all fit the same formula when it comes to the question of a sustainable city form. Additionally, the contextual *indicators* are meant to evaluate the intervention process of IMM. In this case, the performances of an existing context before and after the modification process are needed. 'After all, we are generally confronted not with the task of planning and designing new towns and cities but, rather, that of re-planning and redesigning existing cities, towns and settlements to make them more readily sustainable' [5]. However, eventually designers could use global and standard *indicators* to observe how the city performs respect to other cities.

4.1 Porosity

Superimposition of *volume* and *void* layer defines the porosity (Fig. 1). 'The *volume* layer clearly defines the presence of this principle layer; the urban conveys the physical meaning of the city. Indeed, one can imagine the city as a solid porous *volume*, sponge like, with various sizes of holes linked by linear *void* layer; whereby the integration of these two layers, urban *volume* and *void*, is porosities [1]'.

The density could be categorized as an indicator associated with this porosity. The built-up space *volume* ratio to total the area of the site, the ratio between areas of the buildings to the intervention site area and the inhabitant's ratio to the *volume* and area could all be considered as density *indicators* in the IMM. Optimization of this FLS is contextually dependent, as previously underlined.

The porosity, alike the other KCs, has an optimal span; henceforth, there are optimal limits for the maximum and the minimum of porosity. The optimal span is clearly based on the contextual drivers, e.g. the other KCs, and changes according to the different contexts. The optimal span of every KC highly depends on the vertical relation with other KCs. The density's best condition is highly related to the KC, i.e. efficiency, which is connected to the infrastructural potential of the system.

4.2 Proximity

One of the possible ways of evaluating the proximity is the number of different types of key functions in a predetermined distance; in fact, the predetermined area is walkable scale [15]. In other words, proximity is highly related to the pedestrian fruition of a space; the number of key functions type that one can reach in walking distance. Key function types are educational spaces, administrative services, entertainment, commercial, business, etc. In the evaluation process, proximity is dependent on the number of key function types; whilst it is independent from the quantity of each of the key function types by itself.

Despite the fact that the proximity is independent from the number of people and residence in the neighbourhood, another possible way to evaluate the proximity could be explicated by the relationship between the number of job availabilities and the number of dwellings within the predetermined walkable distance (Fig. 1).

4.3 Diversity

The integration of the *void* layer with the *function* layer creates the diversity of the city, which has a direct relationship with the number of the nodes and *links*. As a result, the more these nodes are bonded to the each other within different networks, the more it makes the system more diverse and complex. One can explain it as a number of interactions between nodes within a network; it could be seen as a number of *links* between the networks' nodes. The diversity, the distribution of the different functions in public open spaces as well as indoor, such as urban piazzas and shops, coincides with the probability of different urban activities and occurrence of the public to encounter and mingle for social and economic events [1]. Diversity is dependent on the number and type of the functions and independent from the distance; however, in order to simplify it, the diversity could be measured as the number of different types of key functions in a predetermined distance. Despite the proximity evaluation, not only is the number key function types important but also the quantity of each key function is counted.

'Diversity face-to-face human interactions on the stage of public life are extremely relevant for supporting liveability, safety and control, economic development, participation and identity' [16].

The ingrowth of the number of members within a *CAS* system is coincided with the diversity level escalation, due to the increment of the nodes and *links* numbers. However, there is a limit for the diversity, alike the other KCs. In the *CAS* system, the number of elements is directly proportional to the *complexity* level, which leads to an increase of the system's efficiency; nevertheless, the overcrowding of the system would hinder the movement of goods and data by decreasing the *connectivity* between the elements. This congestion leads to a dramatic decline in the system's efficiency. Thus, there should be a balance between the *complexity* and *connectivity* within the *CAS*. The balance between *complexity* and *connectivity* requires a symbiotic relation and a *vertical modification* between layers. Thus, the phenomenon has been discussed in the second level of integration division of this research.

4.4 Interface

The integration of the *void* layer with the transportation layer creates the interface, which has a direct relationship to movability inside the urban morphological cavities. The interface feature is the movability inside the building blocks. The permeability of the urban fabric is highly related to another KC, the porosity. One might categorize interface as a feature of the porosity key category. However, the interface is about movability inside the urban *voids*, both pedestrian and motorized, and it defines how complex they are; on the other hand, the porosity main concern is urban *voids*, even if they are closed courtyards. Due to this fact, the interface increases the *complexity* of the system, by increasing the number of possible *links* to connect two nodes; whilst the porosity concerns about how compact an urban fabric is. In order to increase the interface two different actions are requested: first of all increasing the fractal *complexity* of the urban porosity by linking *voids* and making a complex hierarchy of networks, then creating pedestrian walking scale porosities.

To increase the interface, most blocks must be short; that is, steers and opportunities of turning the corner must be frequent [17]. To be clear, one of the main generators of diversity is the *complexity* of urban morphology and buildings typology. The complex configuration of *void* and *links*, interface and porosity, increases the diversity of the neighbourhoods.

4.5 Accessibility

The integration of function and transportation creates the accessibility, which refers to the ease of reaching destinations. People, in highly accessible places, can reach many other activities or destinations quickly; people living in inaccessible places can reach fewer places in the same amount of time. Unlike the proximity, which depends on the distance parameter, accessibility is a distance-independent parameter that simply relies on a time factor.

As mentioned, the accessibility is the integration of the transportation layer and the function layer; hence, the symbiotic relation between these two layers comes to its own, if one wants to improve the accessibility of a place.

Accessibility is also highly related to the available technology in the context. Even though the distance has remained the same between Rome and Milan, nowadays both cities are more accessible to one another. It is necessary to point out another variable, such as the means of transport, high speed trains, in this specific case. The time dependency and distance independency are the main characteristics of this key category.

4.6 Efficiency

The integration between transportation and *volume*, efficiency, is a complicated feature, mostly related to the economy. A possible and simple definition could be explained through the ratio between the number of trips operated by public transport and the total transportation demands of the study area. It means that efficiency could be evaluated by a classical ratio between supply and demands in the public transportation sector. As well as other KCs, the *horizontal modification* of the transportation layer, as well as its vertical optimization, or integration with other layers, have to be implemented in both local and global scale. In other words, the efficiency of the neighbourhoods could not be improved without considering the entire urban transportation's system.

5 SECOND LEVEL OF SUPERIMPOSITION

The results of the symbiotic integration of the preceding part, or second level of superimposition (SLS), depict the KCs, e.g. *compactness*, *complexity* and *connectivity*, which are morphological, typological and technological features of the city (Table 1).

As briefly mentioned, the sustainable form could be achieved through a correct balance between the second level KCs, such as the *compactness*, the *complexity* and the *connectivity*. Any of them would not be sufficient on its own to achieve the sustainable form. However, the balance between these second level KCs is the foundation of a sustainable urban form.

5.1 Compactness

The compactness of the city is defined by the integration of proximity and porosity, which are second-level integration of *volume*, function and *void*. How dense or diffuse is a city and how close or far different functions are within the city, describe the *compactness* of a city. This morphological aspect has a great effect on the final energy consumption of the city. 'The idea of the compact city was integrated into the concept of sustainable urban form, which includes *compactness* amongst other aims such as sustainable transport and a diversity of potential activities within a neighbourhoods' [18]. However, the *compactness* itself does not make a city or neighbourhoods sustainable; the combination of *compactness*, *complexity* and *connectivity* can favour the creation of a more sustainable urban context. Additionally, the optimal level of *compactness* should be considered and based on contextual concerns, so as to avoid any physical or data *connectivity* congestions. This kind of *compactness* has been evidenced in European and Asian historical centres. A possible way to interpret *compactness* could be land use efficiency, which is an optimized solution between *volume*, *void* and function layers. The 'compact city' is characterized by high densities and relatively shorter distances, as meant to accommodate urban development while minimizing the use of undeveloped land, European old towns for instances. Conversely, Sprawl 'Urban sprawl' is the large and low density of the city expansion towards urban suburbs.

The notion of *compactness* has been interpreted as the sustainable form by many designers and planners. This idea of form has caused controversial debates among planners and designers; moreover, its definition is ambiguous, has many different meanings for different designers and makes it impossible to circumscribe its advantages and disadvantages. So now the author of this text will try to express his own idea on *compactness* and its optimum level.

Compactness limits: The controversy about *compactness* raises a question about its limitation. *Compactness* is a double-sided sword; it is obvious that it could have some defects of sustainability, despite its remarkable advantages, if the *compactness*' limits are not properly considered. On one side, higher densities assist to make the provision of amenities and facilities economically viable and enhancing the social sustainability; however, a compact city may become overcrowded and suffer a loss of urban quality. In these circumstances, less open spaces, strong congestion and pollution may not represent an ideal environment in which to live [19]. It has been explained that the *compactness* limit is highly related to other layers, like *complexity* and *connectivity*. Due to this fact, alternative KCs should be considered before discussing whether the *compactness* is of right form or not. For instance, it is believed that congestion is not caused by density or *compactness*, whereas it is *connectivity* that provokes it. A large amount of data can be transferred through different nodes, if only the *links* have proper bonds' width. Conversely, even minimal data could create congestion if the link and connection are not well designed. J. Jacobs admits that the density and diversity do not affect congestion; whereas the traffic congestion is caused by vehicles. 'The apt choice of density accommodated in an urban porosity could be a controversial issue. It is highly related to the contextual circumstances. This choice has to be calculated according to the contextual performances and initial demands' [17].

Comparing compactness and complexity: Here, the authors will try to delineate the *complexity* and *compactness*, through a brief explanation and comparison between the two. The scale and the hierarchy of *links* and nodes, as discussed, could be taken as the main distinguishing feature of the *complexity* and as the trigger that leads the system to the *complexity* [20]. Accordingly, the notion of the multi-centrist is closer to the definition of urban *complexity*. Thus, the equal weighted centres, without scale and hierarchy, would not be enough to create the *complexity*. *Complexity* is made out of a function, nodes and *links* as well as an interface that increases the probabilities of the heterogeneous elements exposure.

The increase in *complexity* in the city involves increasing the mixture of urban uses and functions, which allows unrestricted access to the city. As mentioned in the section about '*compactness*, the urban sprawl of the city does not allow citizens to have easy access to the city's facilities' [6]. Indeed, the *compactness* is not sufficient on its own and should be accompanied by *complexity* and *connectivity*. There is who believes if *compactness* and *complexity* come together, then sustainable form emerges.

5.2 Connectivity

The integration of accessibility and efficiency, or superimposition of *volume*, function and transportation layers, draws attention to the *connectivity* aspect of the city. *Connectivity* is highly related to the transport of goods and data. This new dimension of information and data connectivity clearly correlates diversity and features of the complex system in a vertical way [15]. 'To achieve a well-functioning and economically viable network of public transport, it is required a review of land use's policies, the population density and form, and the structure of city' [5].

Connectivity and compactness: *Connectivity* plays the major role in the prevention of data and movement congestion. The *connectivity* is the main issue to contradict who thinks that *compactness* is not a sustainable form. They believe that the *compactness* lowers the efficiency of the system, triggered by the congestion of the data and objects. As mentioned, in the *compactness*' limits, concentration does not create the congestion. Moreover, the *connectivity* and the *compactness*'s integration complement each other; so accessibility, favored by public transport, reduces the distance from central areas.

6 INTERVENTION

The main intention of the IMM process is actually to focus on the morphological transformation of the system from its current form to a more efficient one. The current form is stable at the stability point of B, with the determined level of the performance; in fact, what the IMM intends to do is propel the urban system transformation to depart from the stability point of B to the point C.

Following 'the theory of catastrophe' by Rene Thom, the departure from point B to C, as seen in Fig. 2, occurs when the context state 2 reaches its instability condition or chaotic threshold, triggered by the modification of the individual elements within its context state [11]. Sergio Crotti asserts that the urban morphological transformation occurs when the existing elements of the dynamic system reach the unstable conformation phase [21].

The IMM process highlights the transformation of mid-scale area, which is a determined area and acts as a bridge between the local (minor) scale and global (major) scale. However, the limit of this

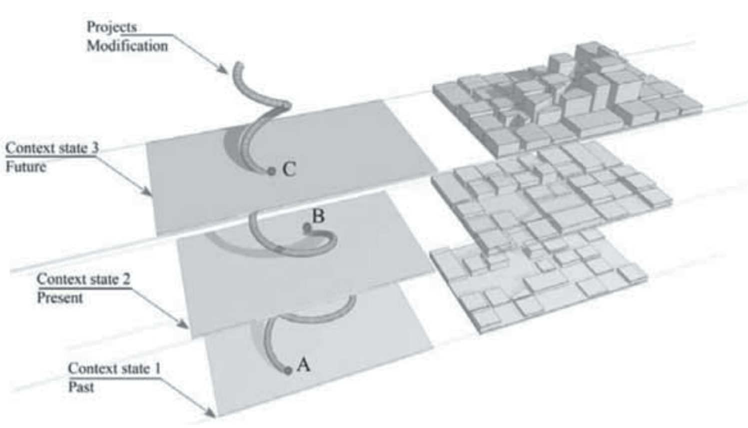

Figure 2: Intervention: spatial relation between context, time and project. The stability thresholds are indicated by letters A, B and C. The IMM intervention focuses on the transformation of the point B to the point C. The yellow A stands for the past, the blue B for the present and finally the purple C represents the future form.

area has to be mapped, as the intervention and project site by the designers and planners. The main criterion to confine the intervention's border is based on contextual feature of the wide-ranging social layer and functional layer, such as morphological aspects. However, in the neighbourhood scale, the proximity of the functions plays a key role.

Detecting the catalyst: The main purpose of the *Hypothesis* phase is to detect the transformation *catalyst*, thanks to the KCs and their associated *indicators*. As discussed, the malfunction of the KCs boosts the modification process. In this phase, the *Key categories*, with the consideration of the interventions' goal, are evaluated and compared with the rest of the urban fabric; thus, the intervention process could be initiated with the modification of the malfunctioning system.

7 INTERVENTION PHASING

The IMM is a multi-stage, iterative process, applied to urban complex systems, for improving the complex adaptive systems' performance, which comprises different but full integrated phases. They are as follows: the preliminary phase is named *Investigation*, whereas the second phase is called *formulation*. The third phase is a design and modification phase, whereas the last phase is retrofitting and optimization (Table 2).

7.1 Phase 1: investigation/analysis

This aspect investigates the actual configuration and the characteristics of a specific urban *CAS*, whenever considered in a provisional state, and effects of an endless transformation process. Since the study's main concern is devoted to the urban morphology and energy consumption of the city, the

Table 2: Different phases of the IMM.

1	1a	Horizontal investigation	Dismantling the system to investigate	Investigation/ analysis	Investigation
	1b	Vertical investigation	The actual value of key categories		
	1c	Actual environmental performance of the system based on 10 indicators		Actual CAS measurement	Measurement
2	2a	Detection of the transformation's *catalyst*		Hypothesis	Formulation
	2b	Assumption of the 10 IMM design ordering principles		Assumption	
3	3a	Horizontal modification	The *catalyst* drives the local transformation; changing the structure of the layers/ligands	Modification	Intervention and design
	3b	Vertical modification	Local transformation acts globally, changing the entire system's configuration	Transformation	
4	4a	Performance of the new CAS based on 10 indicators		New CAS measurement	Retrofitting
	4b	Local modification/optimization of new CAS physical components or subsystem, such as: voids, built spaces, functions and transportation		Design/ transformation	Optimization
	4c	Universal indicators		Comparison	

involved subsystems and their specific correlation affect the urban form as well as energy consumption. The comprehension of the configuration of the involved subsystems and their *links* play a significant role in the IMM final result. Furthermore, the current structure of the system can be considered as just a temporary configuration produced by the preceding *superimposition* processes. For the investigation phase, the designer activates a disassembling procedure of the *CAS* (*horizontal investigation*) into its main physical components or subsystems, such as: *voids*, built spaces, functions and transportations. Each subsystem will first be described on its own in order to describe its individual structure and characteristics, respectively, on a morphological, typological and technological point of view. Then, the correlations '*Links*' between the subsystems will be analysed in a more specific *Vertical investigation*, through special features expressed by the *superimposition*, or symbiotic integration, of the *CAS* subsystem and named *Key categories*. The main outcomes of the investigation phase are:

- Comprehension of the physical arrangement of the CAS.
- Appraisal of the role and value of the key categories.
- Evaluation of the current energy performance of the CAS.

7.1.1 Horizontal investigation (Step 1a)

The first step of the *Investigation* phase is the *Horizontal investigation*, as a preliminary and local analysis made disassembling the *CAS* components (Table 3). Actually, the analysis of physical assessment of the subsystems (*volume* layer; *void* layer; functional layer; transportation layer) starts describing them separately, in order to observe their individual characteristics and understand the urban configuration (morphology) as well as the socio-cultural space (typology) and therefore the artificiality of the space (technology).

7.1.2 Vertical investigation (Step 1b)

The second step of the *Investigation* phase is an investigation of the comprehensive configuration of the *CAS*. For this reason, a particular attention is requested to describe the correlation between the different subsystems (Global configuration) in order to assign a proper role and specific characteristics to each one (Table 4). The main goal of the *vertical investigation* is to understand the architecture of the *links*, and how the system's components (voids, built spaces, functions, transportations) are interrelated.

7.2 Phase 2: interpretation/*assumption: formulation*

This second moment of the IMM process called *formulation* phase anticipates the design phase and it is highly connected with it. It is halfway between investigation and design steps; the integration

Table 3: Procedure for the system's dismantling (The suggested formulas are still under the evaluation by the authors).

Horizontal investigation	Volume	Built volume density, dwelling density, human density	$V_l = V_{built}/area$
	Void	Open space area	$V_d = V_{open}/area$
	Function	Job density, number of legal entities in the intervention area	$F_n = J_{number}/area$
	Transportation	Number of carried out urban trips	N_{tr}

Table 4: Procedure for the system's dismantling (the suggested formulas are still under the evaluation by the authors).

Vertical investigation	Porosity	Factuality of urban voids [9]	$P_s = cat^{-1} \sum \left[1 - \left(n_i x_i A^{-1}\right)\right]^2$
	Proximity	Number of key functions within walking distance area from the dwellings	$P_X = \frac{\sum_{i=0}^{N} nj}{N}, S$
	Diversity	Diversity of subdivision use [9]	$D_1 = \frac{c}{c-1}\left[1 - \sum_{i=0}^{c}\left(\frac{ni}{N}\right)^2\right]$
	Interface	Cyclomatic complexity of pedestrians [9] (L: number of links, number of nodes)	$\mu = L - N + 1$
	Accessibility	Number of available jobs reachable in 20 min, number of available public transportation mode in the area	N_{Acc}
	Efficiency	The number of public transportation trips and the total number of trips	$E_f = N_{ptr} N_{tr}^{-1}$

phase is essentially dedicated to establish a supposition/*hypothesis*, like a possible way for structurally modifying the *CAS* in order to achieve improvement in terms of quality and performance. Consideration of how to fulfill the initial intentions and simultaneously in order to reach the final goal plays the main role in this phase. As mentioned, the configuration of the *CAS* emerges through local modification and integration of the system's components; therefore, the effect of the local modification (on selected layers) plays a great role in the entire system's performances, thereby changing the final *CAS* global configuration. In other words, after the investigation phase, the IMM process comes out with an idea (*Assumption*) about a possible local modification (improvement) of the chosen subsystems that makes the global transformation of the entire system (i.e. *CAS*) possible. The choice of one *subsystem* (layer) as a first driver of the transformation is the main goal of this phase, assigning, respectively, the *catalyst* role to the selected *subsystem* and the *reactant*s function to the others (Fig. 3).

The principal outcomes of this *formulation* phase are (Fig. 4):

- The choice of a catalyst as a supposition based on the knowledge obtained by the previous phase and dedicated to explain the CAS configuration as well as its behaviour and performance.
- The assignation to each subsystem the role of *catalyst* or *reactants*, respectively.
- Preliminary control of the local consequences of the choice.

7.2.1 Choosing the catalyst

The *CAS* is composed by a hierarchy of multiple levels of organization. Considering that on any particular scale, the system is actually a sub-system, the cross-scale effects have a great significance

Figure 3: Investigation and detection of the catalyst; (left) Barcelona, horizontal investigation of the void layer: the public and semi-public open space network of the city; (right) the diversity map of Barcelona is illustrating that 22@ district, mapped with white border, has a low level of diversity with respect to the rest of Barcelona. Due to the investigation phase of actual configuration and the characteristics of the urban context, the catalyst for transformation of 22@ district of the city of Barcelona is detected. Thus, the functional layer represents the catalyst role in order to create more mixed uses and diverse district in further developments. *Diversity map courtesy of Frances Magrina, Maccaro 2002*.

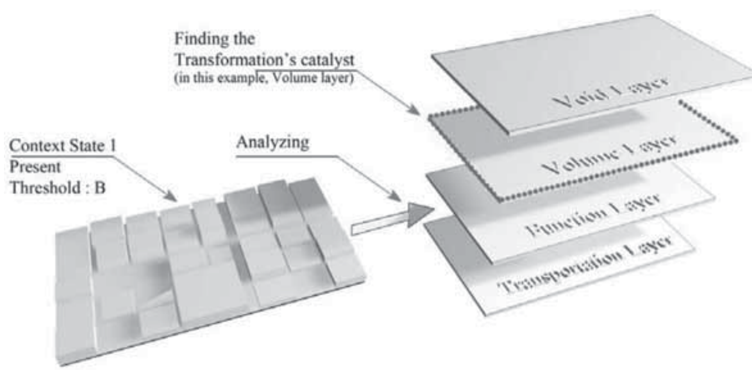

Figure 4: Assumption and interpretation phase. The existing system performance is evaluated, by analysing the system components, through the use of the key categories. In this phase, the malfunctioning layer would be the transformation *catalyst*. The volume layer is indicated as the *catalyst*.

in the dynamics of the *CAS*. Meanwhile, the chosen *catalyst* plays a tremendous role in the IMM. From the selection of one layer (subsystem), the reaction of the system starts, driving the local modification and activating the system's transformation. It is clear that the choice of the *catalyst* depends on the investigation phase.

7.2.2 The role of the DOP (ordering principles) in IMM

In this second phase, a great role is played by the design ordering principles (DOP). The DOPs are tools/instruments used to arrange the structure of the CAS. The way in which these principles are applied affects its structure and performance. One should bare in mind that the 10 DOPs are associated with the 10 indicators that were used for the estimation of the actual energy performance of the

CAS (data collection – Step 1c) as well as for the CAS retrofitting process (Step 4a – second measurement). The DOPs are, respectively:

- Balance the ground use.
- Fostering the local energy production; building as components of community energy system.
- Promote walkability.
- Fostering mixed used spaces.
- Create connected open space system and protect urban biodiversity.
- Promote cycling and reinforce the public transportation.
- Change from multimodality to inter-modality concept.
- Convert the city to a food producer.
- Prevent the negative impact of waste.
- Implement water management.

7.3 Phase 3: modification/transformation, called intervention and design

The third step of the IMM is a specific design phase that involves the *FLS* and applies to a multi-layer and multi-disciplinary approach. Thanks to a driver (*catalyst*), a local modification (*Horizontal modification*) marks the starting point of a chain reaction (*Vertical modification*) towards the global transformation of the *CAS*. Actually, due to the fact that *CAS* is composed of four subsystems, we consider its state as a superposition of products of the subsystems' states. Once the subsystems interact, their states are no longer independent. In urban terms, this phase is oriented to the local modification (neighbourhoods/local nodes) with the aim of global transformation achievement. According to the IMM, in this phase, the project works horizontally (modifying the local subsystems individually) and vertically (modifying the other subsystems and the architecture of their connections). Folding and superimposing the selected layers collaboratively in a way in which the transformation of each layer changes the other one's structure/performance and characteristic is the key factor of the main system transformation. Eventually, a new structure of the system will emerge when all of the superimposed layers meet each other and they integrate together simultaneously and collaboratively; as a consequence, a new system with enhanced performances will be emerged. The main outcomes of this phase are:

- The design/project of the chosen catalyst layer in order to achieve a local modification that will be transmitted to process the reactants layers.
- The local transformation towards a structural transformation of the CAS.
- Preliminary evaluation of the transformation.

7.3.1 Horizontal modification; the *catalyst* phase (Step 3a)

Horizontal modification is the first step of the design phase and its main goal is to modify the selected layers, elected as *catalyst* of the transformation. So the design process starts with Local modifications of the *catalyst*'s layer structure. The local modification as designed perturbation of a system causes a series of effects that lead to macroscopic consequences starting up a chain reaction which can transform the *CAS* structurally. Actually, IMM considers that the *CAS* not only depends on the individual components but also on some interactions between them. This creates emergent patterns as well as specific characteristics and different performances of the *CAS*.

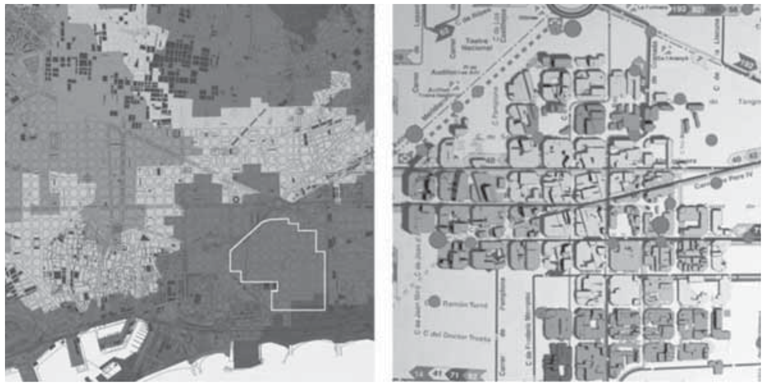

Figure 5: Accessibility map; (left): the actual situation of the 22@ district, outlined with white border, in comparison with the rest of the city of Barcelona, *courtesy of Ajuntament de Barcelona*; (right): the proposed improvement of the accessibility of the district after the modification process. Green stands for highest level of accessibility, 0–20 min to the closest transportation hub or metro stop; yellow indicates for 20–25 minutes, red stands for 25–30 min.

7.3.2 Vertical modification; the reactants (Step 3b)

The *vertical modification* is a chain reaction of the system propelled by the project. The aim of this step is to make possible the propagation of local changes towards the distant parts of the system as a consequence of *connectivity*, and making this propagation the cause of a global change (Fig. 5). The *vertical modification* is driven by the response of the *reactants* layers as catalysed by a selected layer (catalyst) which modifies the architecture of the ligands thereby activating the reaction that transforms the structure of the system. Actually, the system's components are strongly connected, almost to all of the other components, so that simple local changes in their structures can influence the other subsystems and members. Like in a chemical conversion, the *catalyst* layer catalyses the other *reactants,* adjusting the architecture of their joints and transforming the system (*CAS*) structurally.

7.4 Phase 4: second CAS measurement named retrofitting and optimization

The last step is oriented towards the evaluation of the performance of the new *CAS* as a new energy-using complex system, which comprised modified subsystems, in its own new formal configuration; thus, this new configuration will become the new context (formal structure) available for new transformations, since the transformation is an endless process. The new provisional *CAS* will be evaluated and compared with the old one using the 10 *indicators* applied in the Step 1b. After the retrofitting process, the last phase named local modification/optimization of new CAS physical components or subsystems, such as: voids, built spaces, functions and transportations.

7.4.1 New CAS measurement (retrofitting Step 4b)

Once the transformation has occurred, a new CAS measurement as part of the retrofitting process starts. The process is based on the comparison between the new CAS performances and characteristics, and the previous one. This second measurement and comparison evaluate the transformed system's performances. In order to carry out this measurement, some indicative tools are required.

Thanks to these 10 *indicators*, it is possible to compare the characteristic performances of the system, before and after the transformation process. Moreover, the *indicators* help to lead the complex system transformation in a correct way, as well as the result of transformation process.

7.4.2 New CAS local modification (optimization Step 4b)

After the second measurement of the new CAS (retrofitting process) of the results achieved by the transformation, a new systematic optimization procedure starts for completing the transformation with a decisive and final improvement of the system. Actually, a new Local modification/optimization of specific physical components of the already transformed CAS could be necessary for better controlling the results of the previous chain reaction. This final optimization is finalized to improve further the CAS's environmental performances, modifying again locally one or more subsystems, respectively: volumes; voids; function and transportation. These minor and local changes affect again the architecture of the *CAS*, modifying it structurally again but with a better control of the previous transformation's reaction. The final result of this optimization process is a concluding but still provisional *CAS* that configures itself as the new threshold of endless transformation process.

7.4.3 Universal indicators (comparison Step 4c)

Unlike the prior measurement processes, which evaluate the system's performances before and after the design process, universal indicators are tools to make a comparison between the city's performances and other cities.

8 EPILOGUE

The IMM has been introduced as a design method, based on complex adaptive system analysis, to transform an existing urban context into a more sustainable form. The paper solely depicts the method in order to construct a theoretical foundation for further references and citation within practical research and exercises.

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