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The cover image is a train passes a rail road crossing that is surrounded by flooding caused by rain and melting snow in Nidderau near Frankfurt, Germany, Wednesday, Feb. 3, 2021. (AP Photo/Michael Probst)

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Evergreen section

Chaos and chaos: the city as a complex phenomenon

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Evergreen section

This article - published in Italian in 1993 with the title "Caos e caos: la città come fenomeno complesso" as a contribution in the volume "For the XXI century – an encyclopedia and a project" – is published again in this new section of TeMA Journal, Evergreen, in its literal English translation with the addition of new images. This section aims at drawing the attention of the international scientific community to papers that, despite the passing of time, still present elements of significative scientific interest – insights, anticipations and reflections – enough to deserve careful read back.

Abstract

To say that the city is a dynamically complex system is to affirm that the city can be traced back to a set of components in relation to each other (system), that the processes of the system cannot be managed and controlled with deterministic tools (complex system) and, lastly, that the future evolution of the city-system cannot be predicted linearly on the basis of knowledge of the initial conditions (dynamically complex system). The degree of complexity reached by the city, as a modern expression of collective life, is such that it is unable to provide a compatible and adequate solution to the problems of the "city-system", which is subject, like all systems, to processes of entropy maximisation.

Keywords

Complexity theory; Urban system; Entropy.

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Laplacian determinism was slowly replaced by a problematic approach in scientific research in the early twentieth century which, over the years, took shape in rigorous terms: the chaos theory. Deterministic systems[1] even very simple ones made up of a few elements, can exhibit "aleatory" behaviour. This aleatory nature is an intrinsic quality of the system itself and does not depend on the type or amount of information available.

The first insight into randomness is attributable to Henri Poincaré (1903), who observed that "chance" phenomena can occur in a system[2]. This kind of randomness was given the name "chaos" in later times.

One of the principles on which the chaos theory is based is Heisenberg's uncertainty principle[3] according to which "the exactness with which classical concepts can be sensibly applied to the description of nature is limited by so-called uncertainty relations".

This principle, which has become one of the foundations of quantum mechanics, provides a convincing explanation of certain random phenomena on a very small (atomic) scale.

1 "A system is deterministic if exact knowledge of its initial state makes it possible to predict its future with certainty. Let us suppose the laws of physics are deterministic; will we be able to predict the future of the universe in detail, as Laplace claims? In practice, this statement is neither likely nor true. It can be admitted that the universe, which is an extremely complex system, presents the phenomenon of sensitive dependence on initial conditions. If our knowledge of the initial state of the system is even slightly incomplete, our predictions will quickly be subject to considerable error: determinism, therefore, does not imply predictability and the rigour of physical laws does not contradict the contingency of the facts of everyday life". Ruelle, D., "Determinism and predictability" in Le Scienze n.82, Le Scienze S.p.A. Publisher, August 1984.

2 "A very small cause which escapes our attention brings about a considerable effect which we cannot fail to see and so we say that the effect is due to chance. If we knew exactly the laws of nature and the situation of the universe in its initial state, we could predict exactly the situation of the same universe at a later time. But even if it were the case that natural laws no longer held any secrets for us, even then we could know the initial situation only approximately. If this would enable us to predict the next situation with the same approximation, we would not need more and we would have to say that the phenomenon has been predicted, that it is governed by laws. But this is not always the case; it can happen that small differences in the initial conditions produce very large differences in the final phenomena. A small error in the former produces a huge error in the latter. Prediction becomes impossible and you have a chance phenomenon". Poincaré, H., "Science et Methode", Flammaron, Paris, 1908.

3 "Thus today's science, more than the previous one, has been imposed by nature and the ancient problem of grasping reality by means of thought must be posed anew and solved in a quite different way. Previously, the model of exact science could lead to philosophical systems in which a certain truth - such as Descartes' cogito, ergo sum - formed the starting point from which all questions concerning the conception of the world had to be addressed. But now, in modern physics, nature has reminded us very clearly that we cannot hope to understand all knowledge from such a firm basis of operations. On the contrary, in the event of any substantially new knowledge, we must always find ourselves in the situation of Columbus, who had the courage to leave all the land known until that time, in the almost insane hope of finding other land beyond the seas". Heisenberg, W., "Mutamenti nelle basi della scienza", transl.it., Einaudi, Turin, 1944, p. 27.

On a larger scale, the reasons for unpredictability have rarely found valid scientific verification; the random motion of fluids is an exception that confirms the rule. However, it is not necessary to resort to such complicated systems in order to verify the existence of random behaviour, which is also found in relatively simple systems.

In general, the pre-eminent characteristic of a chaotic system is its high sensitivity to even the smallest actions that can occur at any point in its being and becoming. Thus, the degree of uncertainty that a chaotic system can reach is extremely high and, in addition, any phenomenon, even insignificant ones, can very quickly reach macroscopic proportions. In other words, in the presence of chaos, any prediction can reach significant inaccuracies.

The dynamical systems theory can be regarded as the indispensable support in the development of the conceptual framework for the study of "chaos"[4]. The definition of a dynamical system is given by the elements and the relationships between the elements of the system, as well as the laws and criteria of evolution (of the state) over time. The space of existence of the system's evolution is known as the space of states or the space of phases; this space is a purely conceptual abstraction, the coordinates of which are the components of the state.

Of course, the coordinates of the phase space change with the context; for example, for a mechanical system, they might be found in position and speed, for an ecological system in the populations of the various species. Although it is recognised that the behaviour of chaotic dynamical systems is unpredictable, the space of states can be useful in representing this behaviour in geometric form.

[4] "An apparent paradox is that chaos is deterministic, i.e., generated by fixed rules that, in themselves, contain no random element. In principle, the future is completely determined by the past but, in practice, small uncertainties are amplified; thus, although behaviour is predictable in the short term, it is unpredictable in the long run. In chaos there is order: underlying the chaotic behaviour are elegant geometric shapes that create randomness in the same way as a papermaker shuffles the pack of cards or a cook shuffles the dough for a cake. The discovery of chaos has created a new paradigm amongst scientific models. On the one hand, it implies the existence of new fundamental limitations to our ability to make predictions; on the other hand, the determinism inherent in chaos implies that random phenomena are more predictable than previously thought. Seemingly random information gathered in the past (and dismissed as too complicated) can now be explained in terms of simple laws. Chaos enables us to discover order in systems as diverse as the atmosphere, a dripping tap and the heart. This has resulted in a revolution that is affecting many different branches of science. Crutchfield, J. P., Farmer, J. D., Packard, N. H., Shaw, R. S., "Chaos", Le Scienze n.222, Le Scienze S.p.A. Publisher, February 1987.

At present, chaos theories do not provide a solution to the problem of predicting the evolution of systems, mainly because there are still many unknowns about the actual incidence and significance of chaos. However, it is unequivocally agreed that one measure of chaos is entropy.

The concept of entropy is based on the second law of thermodynamics: every time energy is transformed from one state to another, the available energy is reduced in favour of the unavailable energy. To use Rifkin's definition, one can say that the transformation of energy requires "paying a price". Yet again, "this cost is represented by a loss of energy available to perform work of a certain type in the future. The term that describes this fact is entropy. ... An increase in entropy, therefore, means a decrease in available energy"[5]. When energy (and matter) become unavailable, the result is the greatest possible disorder and, thus, chaos.

The second principle of thermodynamics[6] refers, not only to energy, but also to order and, above all, to the organisation of systems; in this sense, this (principle) applied to a physical system is defined as a statistical principle of energy degradation, of disorder of the constituent elements and therefore of disorganisation.

Thus emerges the centrality of organisation as an intrinsic quality of complex systems[7].

[5] See Rifkin, J., "Entropy", Arnoldo Mondadori, Milan, 1982, pp.44-45. In the same pages, Rifkin, making the terms of his statements explicit, reiterates: "Let's take a car engine as an example. The energy in petrol is equal to the work done by the petrol engine, plus the heat generated, plus the energy in the exhaust products. Again, the most important thing to remember is that it is not possible to create energy. No one has ever succeeded in creating it and no one ever will. The only thing that can be done is to transform energy from one state to another. It is difficult to understand this concept if one does not consider that everything is made up of energy. The appearance, form and movement of anything in existence is really only an expression of the different concentrations and transformations of energy. A person, a skyscraper, a car and a blade of grass all represent energy that has been transformed from one state to another".

[6] The pervasiveness of this principle and, in general, the growing popularity of certain fundamental concepts of the main scientific theories can be seen in the countless quotations and references in recent popular scientific literature. Amongst them, attention is drawn to the effective trivialisation of the entropy constraint by L. De Crescenzo in a widely circulated popular text ("Il dubbio", Arnoldo Mondadori Editore, Milan, 1992, p. 57 ff.): "When God expelled Adam and Eve from the earthly paradise... he said: You man will work with sweat and you woman will give birth with pain! Then, when he saw them coming out of the gate, he cast the last anathema on them: And both of you will be haunted forever and ever by the Second Principle of Thermodynamics!"

[7] "We are surrounded by complex objects, but what is complexity? Living organisms are complex, mathematics is complex and the construction of a space probe is complex. But what do these things have in common? Likely the fact that it contains a lot of information that is difficult to obtain. We are currently unable to create living organisms from scratch, we have great difficulty in proving certain mathematical theorems and we need a lot of work to conceive and

Organisation can be defined as the form, distribution and intensity of the relationships between the components that make up a complex unit or system. Ultimately, the ability to organise is one of the fundamental properties of a system and can be expressed as the evolution of relational interactions into organisation.

Organisation[8] thus becomes the constituent property of a system.

The variety and multiplicity of existing systems makes it possible to build a hierarchy and categorisation of systems. The determination of the hierarchical level of a system depends essentially on the choices and decisions of the observer, on which the very conceptualisation of a system ultimately depends. In other words, in the definition of a system, there are always, at the base, decisions and choices of a subject, which operates within the polysystemic interior of the selections in relation to its own aims, to the available tools and in relation to the cultural and social context.

However, the chaos theory also implies degrees of complexity within the scientific method of testing a theory; until now, the classical method involved making predictions and then comparing them with experimental data. For chaotic systems, the impossibility of making long-term predictions means that the verification of a theory becomes a very delicate activity full of pitfalls, relying on statistical and geometrical properties rather than detailed and precise predictions.

Amongst the infinite systems into which physical reality can be broken down, it is indispensable, for the renewed and extended purposes of the most recent "research" on the territory, to consider the city as a dynamic system of high complexity.

To say that the city is a dynamically complex system is to affirm that the city can be traced back to a set of components in relation to each other (system), that the processes of the system cannot be managed and controlled with deterministic tools (complex system) and, lastly, that the future evolution of the city-system cannot be predicted linearly on the basis of knowledge of the initial conditions (dynamically complex system). The degree of complexity reached by the city, as a modern expression of collective life, is such that it is unable to provide a compatible and adequate solution to the problems of the "city-system", which is subject, like all systems, to processes of entropy maximisation.

implement a space probe." It can be concluded that "*an object (physical or intellectual) is complex if it contains information that is difficult to obtain*." Ruelle, D., "Caso e caos", Bollati Boringhieri, Turin, 1992, p. 149.

8 "What is organisation? First definition: organisation is the arrangement of relationships between components or individuals that produces a complex unit or system, endowed with qualities that are unknown at the level of the components or individuals. Organisation interrelatedly connects different elements, or events, or individuals who consequently become components of a whole. It provides a relative solidarity and solidity to these links and thus guarantees the system a certain possibility of durability, despite random perturbations. Organisation, therefore: *transforms, produces, connects, maintains*". Morin, E., "Il Metodo", Idee/Feltrinelli, Milan, 1983, p. 133

Whilst in some periods of urban history the city has developed in harmony and compatibility between its parts, in recent decades, the occurrence of extremely variable and changing events in the urban fabric, which are difficult to attribute to one cause and one alone, has led to unbearable conditions of intolerability and congestion. These conditions are almost always the result of difficult-to-understand causes, accompanied by an inability to control and manage complex phenomena, due, not only to the inadequacy of the procedures adopted, but also to the unavailability of effective tools.

In addition to all of this, the introduction of new technologies, involving all levels and all sectors of associated life, generates new knowledge and new progress. Thanks to these distinctly self-propulsive characteristics, the capacity for affirmation and diffusion of technological progress goes beyond the narrow limits of economic-productive activities and has a profound impact on ways of being and thinking and, therefore, on social, political and, of course, territorial aspects.

In short, the multiplicity, multiformity and variety of existing relationships - in a word, the complexity - within the city-society system requires appropriate methods of interpretation and analysis, as well as innovative tools and control techniques.

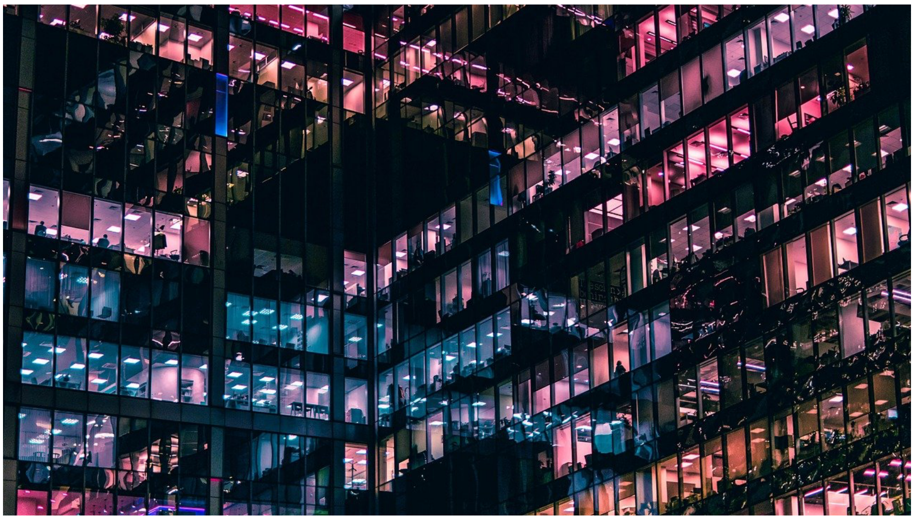
For some years now, scientific research in the urban and territorial field has agreed to consider the city as a "system" defined by the elements (the various urban activities and functions) and by the interactions and relations between its many components (material and immaterial communications) which produce, with different intensities and modalities, effects that are difficult to identify in all parts of the city (McLaughlin, 1973)[9].

In this perspective, the "complexity paradigm" seems to offer greater guarantees of relevance and relationship in the interpretation of the variety and interdependence of urban phenomena and may also assume a central

[9] "Our daily experience confirms that the relationship between man and the environment can be understood in terms of an *ecological system or ecosystem*. In terms of human behaviour, we identify the components of the system as spatially localised activities. Activities interact or are interlinked through physical, or intangible, communications flowing along certain channels. The behaviour of individuals and groups is clearly competitive and is motivated by a constant investigation of the environment which, from time to time, is expressed in actions to modify activities, spaces, communications, channels or some combination of these, or their relationships. Obviously, these processes are complex, both in themselves (i.e., per individual or group) and in the way they can be interrelated; but a certain structural simplification is necessary and possible". Mc Loughlin, J.B., "Urban and Regional Planning", transl.it., Marsilio, Padua, 1973, p.17.

role in the definition of tools and methods for problem solving. A challenge to which the future of the city is entrusted.

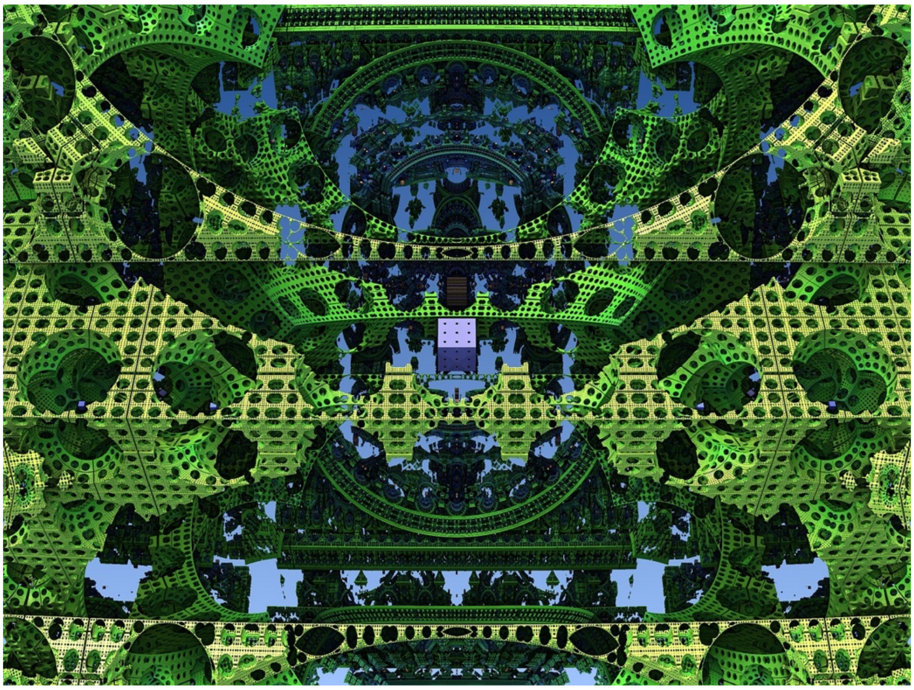
The reading of the city aimed at identifying, not only its physical aspects (its shape, its streets, its houses), but also its functional aspects (the relationships that exist between its components and the laws that regulate these relationships), leads us to adopt and make our own the systemic-procedural approach, oriented, precisely, towards defining the becoming of reciprocal influences between the elements of the system and between the system and its components.



The theoretical support to refer to can be found, *inter alia*, in Thom's theory of catastrophes[10] and Morin's philosophy of heterogeneity, considering the city system as a structure, the state of which is continually modified by the supply of "energy" it receives from the outside and which it consumes incessantly. From this, it is deduced that its state of equilibrium is only apparent given that, in reality, it is in stationary equilibrium or in dynamic stability; that is, the city is a system characterised by an inextricable complementarity between "disordered phenomena" and "organising phenomena", which regulate themselves in a subsequent (only) stationary state of equilibrium.

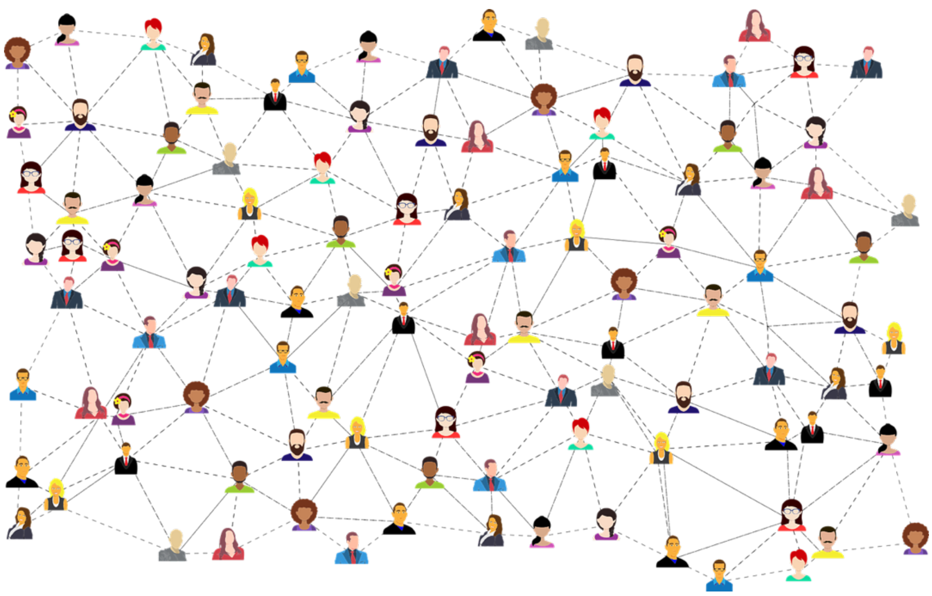
In order to govern such a system, it is firstly necessary to relate its overall structure to an interpretative model made up of intelligible elements and relationships. Once the approach criterion has been defined, it is necessary to know which are the constituent elements and which are the main relationships of the (modelled) system. Lastly, it is necessary to determine the characteristics of the elements and the laws governing their integration, without which (elements, laws and integration) it is not even possible to think of modelling the "city-system".

[10] "The most innovative and relevant qualitative-quantitative approaches, from a methodological and heuristic point of view, are René Thom's topological approach of the "catastrophe theory" and the theory of "bifurcations". Both theories study (the first in a more restricted field, but with taxonomic intentions; the second in a more general field) dynamic systems characterised by multiple equilibria, in which the passage from one equilibrium to another may imply a discontinuity, a sudden jump, a "catastrophe" and in which the temporal paths of the variables may under certain conditions present a bifurcation, a clear alternative between trajectories that subsequently follow a different history. In both cases, the time trajectories appear largely irreversible and the system does not return to its initial state when the direction of time is reversed, unlike Newtonian dynamics, which assumes harmonic systems and reversible trajectories. The essential element that arises from these theoretical approaches is *the criticality of the initial conditions* of the system, which follows from the fact that a certain path can only be replicated by chance and that, as mentioned above, it cannot be carried out in the (temporally) reverse direction". Camagni, R., "Economia urbana - principi e modelli teorici" (Urban Economy - principles and theoretical models), La Nuova Italia Scientifica, Rome, 1992, pp. 319 and 320.



The essential characteristic that allows a generic system to exist is what Edgar Morin (1977)[11] calls "organisational antagonism". Every organisational interrelation presupposes the existence and play of attractions, affinities, the possibility of connections or communications between the elements. But the preservation of differences likewise presupposes the existence of forces of exclusion, repulsion and dissociation, without which everything becomes confused and no system is conceivable.

In other words, every system, including the urban system, produces both antagonisms and complementarities within it; to govern a system, it is therefore necessary to know the rules (insofar as they can be found) by which antagonisms and complementarities are organised.



11 "Unlike thermodynamic equilibria of homogenisation and disorder, organisational equilibria are equilibria of antagonistic forces. Every organisational relationship and, therefore, every system, therefore involves and produces antagonism at the same time as it produces complementarity. Every organisational relationship necessitates and *actualises* a principle of complementarity and necessitates and virtualises, to a greater or lesser extent, a principle of antagonism". Morin, E., The Method, trans. it., Idee/Feltrinelli, Milan, 1983, pp. 152 and 153.

Like and before Morin, von Bertalanffy (1968) had stated that every totality is based on the competition between its elements and presupposes the struggle between its parts.
One cannot, therefore, speak of a system without presupposing the idea of antagonism; but this idea carries, as an implicit and direct consequence, "potential disorganisation" or disorder. In fact, the moment the system breaks down, disorder spreads. But the system comes into crisis when differences turn into oppositions and complementarities into antagonisms.
In light of these considerations and in order to better clarify the terms of the question, it is appropriate, at this point, to recall the systemic-functional approach to the city, which is proposed here.
This approach is directly related to the general theory of systems, which, applied to the urban phenomenon, allows for the construction of a cognitive model useful for the interpretation and decoding of urban complexity.
In this sense, as early as in the reading and analysis of the city-system, it is necessary to combine the characteristics of the individual parts with the characteristics of the whole system, with the aim of defining the interrelationships that link the individual parts to the whole and vice versa.
The path (circuit) on which the passage from the parts to the whole and from the whole back to the parts is triggered is of a poly-relational type in that the elements must be defined in their characteristics, in the relations in which they take part, in the overall organisation in which they exist and, ultimately, in that specific "breeding ground" in which they are inserted (that specific system); conversely, the system must be defined in its specific characteristics, in the relations existing between its elements and in the relations with each of its elements.
With reference to this scientific approach and from observation of the urban system, it can be said that the city is undoubtedly a dynamically complex system.
On the basis of the above considerations and the theory of dynamic systems, it can be deduced that the evolution of the city cannot be predicted linearly on the basis of the initial conditions.
To say, therefore, that a city is a dynamically complex system is to say that said system is defined, not only by its own characteristics, but also by laws and criteria of state evolution that change over time.
The dynamic complexity that characterises the city depends essentially on four main variables:

- levels of hierarchy;
- the type and quality of relationships;
- the number of elements;
- the speed and laws of change.

The various levels of hierarchy enable the urban structure to be read from various points of view.
The type and quality of possible relation paths refer to the interconnection between the various elements of the system and depend on the ability to know the range of effects that each action performed, even on a single part of the system, may generate on one or more different parts and on the other relations.
Having thus defined the reference concepts for a "modelling" of the urban system that allows for the identification of reading methods and analysis techniques, the next step must be oriented towards the definition of procedures aimed at governing the "organisation" of the system.
These procedures must allow for the definition of control tools and techniques oriented to the re-functionalisation of the relational sub-system and to the recovery and reuse of the physical sub-system.

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Full professor of Urban Planning Techniques at the University of Naples Federico II. Since 1987 she has been involved in studies on the management of urban and territorial transformations. Since 2004, she has been Member of the Researcher Doctorate in Hydraulic, Transport and Territorial Systems Engineering of the University of Naples “Federico II”. Her research interests focus on the processes of urban requalification, on relationships between urban transformations and mobility, and on the estate exploitation produced by urban transformations. On these issues she has coordinated many research groups as scientific manager of operational units or as principal investigator of competitive projects. As scientific manager of the Dicea-University of Naples Federico II operative unit: “Impacts of mobility policies on urban transformability, environment and real estate market” from 2011 to 2013, as part of the PRIN project; Cariplo Foundation project “MOBILAGE. Mobility and aging: support networks for daily life and welfare at the neighborhood level "2018-2020; ERASMUS + Key Action2: Project "Development of a Master Program in the Management of Industrial Entrepreneurship for Transition Countries" (MIETC), with European and Asian partners 2020-2022. As Principal Investigator of the Smart Energy Master Project for territorial energy management funded by PON 04A2_00120 R&C Axis II, from 2012 to 2015. Author of over 150 publications.

Rocco Papa

Emeritus of Land Use Planning at the University of Naples Federico II. Editor-in-Chief of the Scientific Journal TeMA - Land Use, Mobility and Environment since 2007. Director of the Department of Urban and Regional Planning (DiPiST) of the University Federico II of Naples, from 1999 to 2005. Vice-Mayor of the Municipality of Naples, from 2001 to 2006. City Councilor for Livability (appointed to Town Planning and Historical Centre) for the Naples Municipality, from 1997 to 2006. Research activity, carried out continuously since 1974, has developed according to the following four main lines: the study of the interactions between urban and mobility systems; the management and governance of metropolitan areas; the safeguard of environmental quality in highly urbanized areas; the experimentation of new protocols for urban planning tools connected with the updating of techniques, methods and models of analyses, interpretation, planning and governance of territory. As City Councilor for Livability (appointed to Town Planning and Historical Centre) for the Naples Municipality he has developed in detail the following projects: the approval and implementation of the new Master Plan of Naples, the restoration and requalification of the “Real Albergo dei Poveri” and of the “SS. Trinità delle Monache”, the implementation of the Line 1 and Line 6 of the Metropolitan Railway. He is the author of more than 150 publications.