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THE NETWORK PARADIGM AS A METHOD AND TOOL FOR COMPLEX SYSTEM MEASUREMENT – A CASE STUDY FOR ENVIRONMENTAL OBJECT

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Abstract – Network science is strictly connected to the problems of complex systems, which is also the challenge for modern metrology. The paper points at the common issues within these two domains (network science and metrology), highlights the facts on the inclusion of the former by the later one, and discusses the consequences of such proceeding on measurement of complex systems and metrology, in general. Environmental object of the energy efficient smart house is used for such formulated task as it represent a multilevel and multiscale intricate organization proper for verification of original contributions in a domain of complex system characterization.

Keywords: metrology, complex systems, network theory, environmental measurements

1. INTRODUCTION

Measurement – whether performed by operating thermometers, pyranometers, devices for quantifying air pollution, administering health of human being embedded in surrounding environment – is an activity intended to produce knowledge about the state of an empirical system. In fact, the process where such knowledge emerges doesn't start in the physical act of measurement, when the physical tool (measurement device) is applied directly to considered object, but at the level of conceptual considerations able to provide the fundamental rules for metrology science. Thus, the distance between lack of knowledge and recognizing some objective fact about the object comprise of the conceptual, ontological, epistemic, and technological conditions that make measurement possible and reliable [1]. There have been many works which discussed the issue of suggested distance, proposing the models of this cognition process in metrology and discussing the same role of the model in measurement science [2-4], but finally the problem posed in such way to date is open. What is more, the issue is additionally complicated as the empirical adequacy of the theory or model and the reliability of measuring procedures appear to presuppose each other in a circular way [1]; to consider this statement for example of mass, a link between the theory of mass and reliable method of mass measurement should be established. From the history of metrology point of view, this science moved from reductionism to nonlinear dynamics paradigm, but description of complex system as a whole which consists of many subsystems still is lack of adequate systematics since we are not able to provide quantitative relations among parameters, constituting scientific theories and models. Accoridng to [5], complex system properties now can be discussed mainly in phenomenological regime. For example, one can identify many body systems, broken symmetry, hierarchy, irreversibility, relations, situatedness, integrity, intricate behaviour, etc., but concise statement formulated in language of logic or mathematics are inaccessible for the task of characterisation of the general complex systems. In this way, there are no technical methods and tools adapted to measure them completely and reliably, including the case of environmental measurements.

Scientists typically produce a knowledge about the object identifying phenomena. But phenomena do not necessarily have to occur in a form that is accessible to our perception [6], whereas data are records that are visually detectable [7]. In [8] van Frassen clarified that the range of observable phenomena extends well beyond the realm of sense data to include also data models as "the dress in which the debutante phenomena make their debut". In this context one can use the Suppes's remark that theory is not confronted with raw data but with models of the data and that the construction of these data models is a sophisticated and creative process [9]. In other words, experimentalists brings to theoretician a small relational structure, constructed carefully from selected data. Thus metrology provides the methods and tools to convert qualitative data into theories, applicable to phenomenon (attributes) proper for objects, producing quantitative measure of empirical meaning.

Modern theory of complex networks has grown up with a graph theory, well-known subfield of mathematics since XVIII-th century. Whereas the problem of so called Königsberg bridges undertaken by Euler was inspiring for fundamentals of the graph theory, it was the access to huge amount of data which has triggered the vivid research in complex network domain [10]. But as it has been shown in the following works, network-like structure is not only evident, visible feature of chosen physical systems (see Fig. 1), but also can be perceived as an inherited property embedded in recorded data [11-13]. Thus it is essential to answer the question, if studying network-like relations can produce knowledge about the state of an empirical system. The paper outlines the case study for exemplary complex object of an energy efficient smart house embedded in

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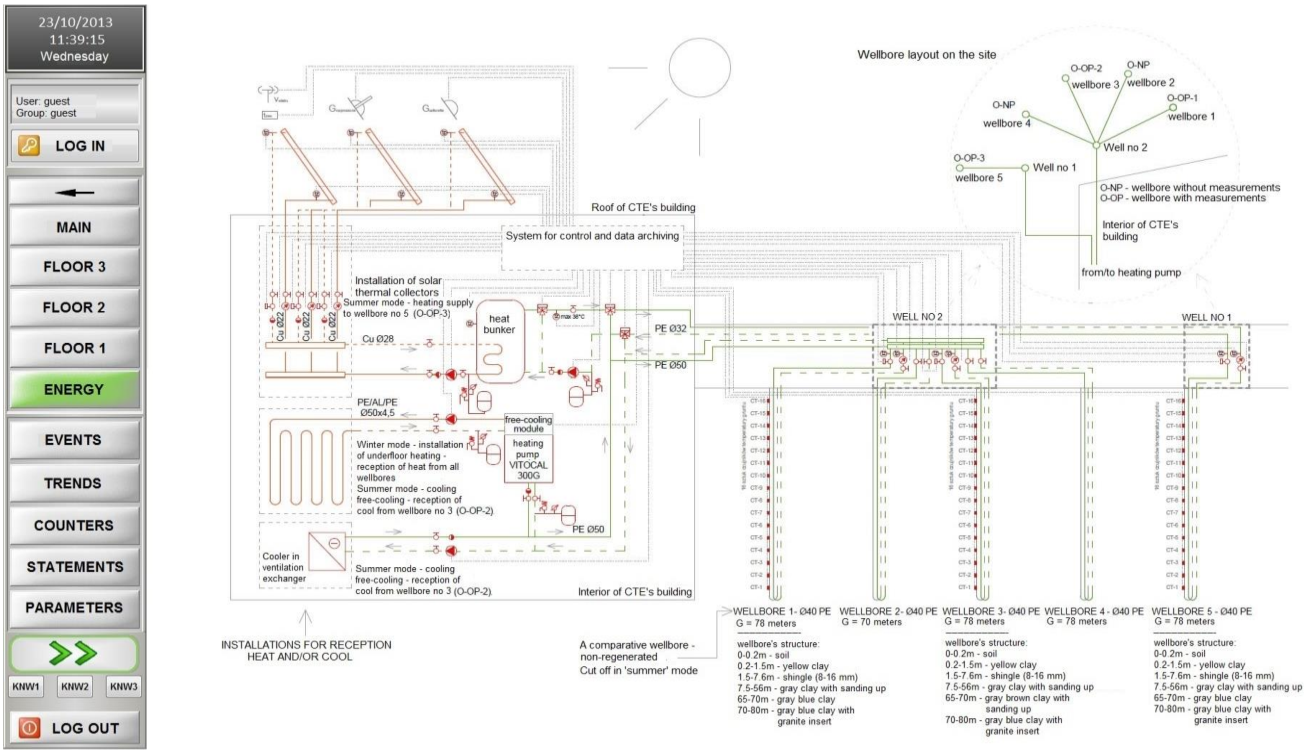

Fig. 1. Example of network in physical world - circuit of the heating system designed for the energy efficient office building.

environmental conditions, proposed to prove the correctness of network paradigm for metrology, which conditions feasibility and reliability of measurement process.

2. SOME REMARKS ON THE COMPLEX NETWORKS SCIENCE

Network science is the field of theoretical and applied interests operating on complex interrelations between the elements, which form generally comprehended the organized structures (the system with identified bounds). The construct of network is the main concept of abstract nature used in this field and with physical expression in the real world. Analogously to the graph, where one can identify vertices and edges, network is perceived as a kind wiring diagram consisted of system's component's called nodes and the direct interactions between them, called links (Fig. 2). Thus, if we want to understand a complex system, we first need a map of its wiring diagram. Then identification and quantification of the characteristic features should be provided within its bounds.

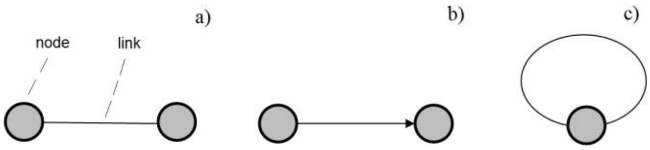

Fig. 2. Graphical representation of edges/nodes in graph/network: a) undirected, b) directed, and c) self-loop.

A network is called directed (or digraph) if all of its links are directed (Fig. 3a) or undirected if all of its links are undirected (Fig. 3b). In a multigraph network nodes are permitted to have multiple links (or parallel links) between them – Fig. 3c, whereas introducing predefined weight parameters into the diagram constitutes the weighted network – Fig. 3d. One can also distinguish a bipartite graph (or bigraph), i.e. a network whose nodes can be divided into two disjoint sets U and V such that each link connects a U-node to a V-node (for graphical representation of bigraph and explanation of its projections see Fig. 3d). Finally, one can also define multipartite networks, like tripartite, etc. Networks can be complete or no – complete network assumes that all nodes are connected to each other (no self-connections).

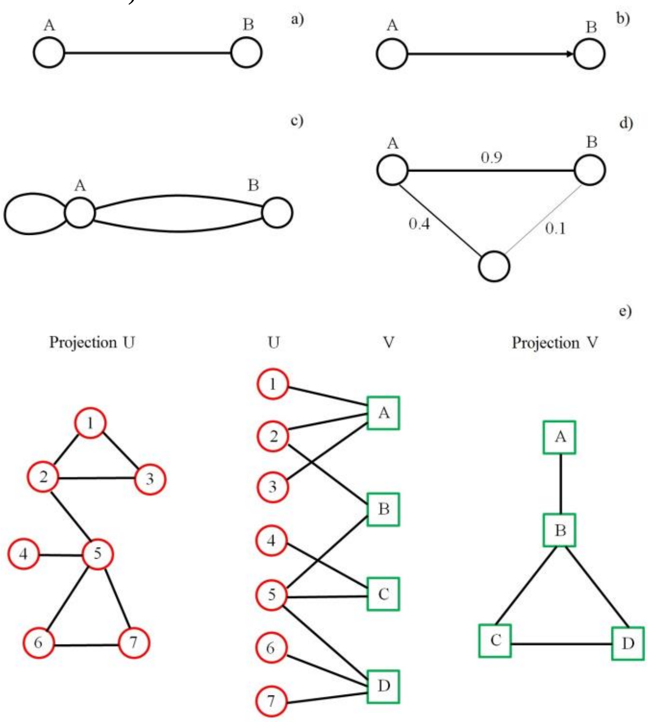

Fig. 3. Exemplary graphical diagrams of complex networks: a) undirected, b) directed, c) multigraph, d) weighted, and e) bigraph.

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There are various measures defined for complex networks, which relate to their topological features, but also dynamical evolution can be caught with the theory of complex networks [10, 14-18]. For example, a degree of each *i*-th node in the network can be measured, which represents the number of links it has to other nodes [10, 16, 18]. Calculation of average degree and degree distribution provides additional insight into the properties of the graph [10, 18]. The same is as regards the network diameter, path length (and/or its averaged value), link density, clustering coefficient, assortativity coefficient, matching index, local degree anomaly, closeness and betweenness centrality, etc. Analyzing the fundamental properties of networks with the use of these abstract indexes (and relations between them) enables formal categorization of that intricate structures. In this way, the systematics of regular lattice, random, Watts-Strogatz (or small-world), scale-free, etc. networks have been created and characterized [10, 14, 15].

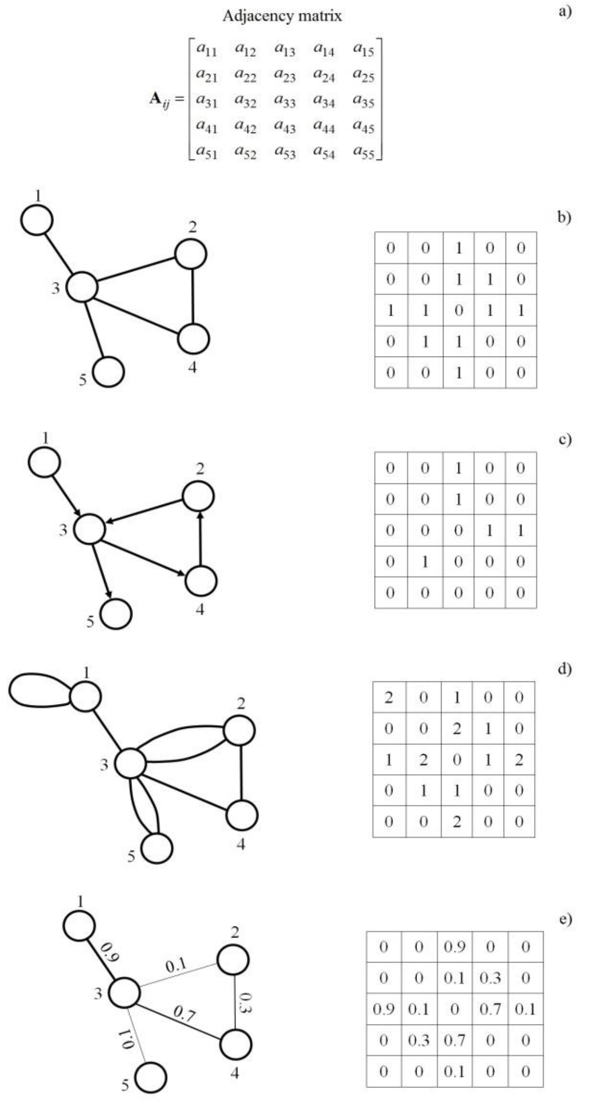

Fig. 4. The general form of adjacency matrix $\mathbf{A}_{ij}$ for the case of network with five nodes a) and its record for undirected b) and directed graph c), multigraph d), and weighted graph e).

In parallel to the graphical description, there has been proposed the algebraic representation of the complex networks which uses the concept of adjacency matrix $\mathbf{A}_{ij}$ [10, 16-19]. Values of elements a_{ij} in the square matrix $\mathbf{A}_{ij}$ of $N\times N$ size (N nodes needs encoding in N rows and N columns) are determined as follows:

- $a_{ij} \neq 0$ if there is a link pointing from node *j* to node *j*; in case of unweighted networks $a_{ij} = 1$ or its multiple (if there are the self-loops in the structure),
- $a_{ij} = 0$ if nodes *i* and *j* are not connected to each other.

The rules were expressed in Fig. 4.

Introduction of the adjacency matrix to the network calculus make easier the algorithmization of the problems in the field of network science, and provide further contributions to the complex network theory, e.g. the fact that in real networks only tiny fraction of the matrix elements are nonzero, which implicates the sparsity of matrix $\mathbf{A}_{ij}$ [10]. It is also the simplest way of representation for network in the computer memory.

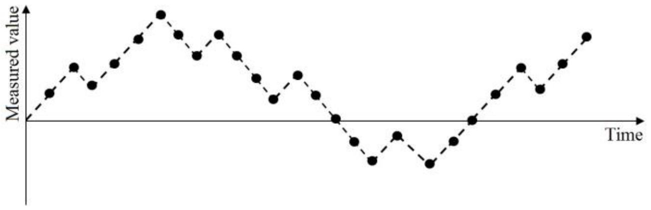

Fig. 5. Measured time series as a one-dimensional chain of nodes.

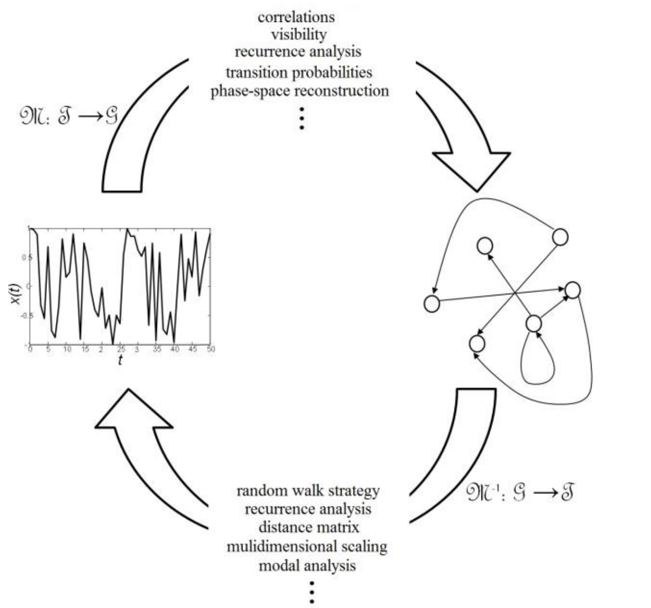

Fig. 6. Scheme of forward and inverse transformation between time series and complex network in the network paradigm.

Next original contribution can be attained when perceive the time series of recorded data as a network-like recording (Fig. 5) with a unique coding of phenomena occurring in the bounds of considered system. This new domain of research in the network science tend towards construction of forward $\mathfrak{M}$ and inverse $\mathfrak{M}^{-1}$ transformation between time series and complex network [11-13] – see Fig. 6. Lossless (almost lossless, because of sampling process [11]) conversion $\mathfrak{M}: \mathfrak{T}\rightarrow\mathfrak{G}$ opens any complex systems with accessible output/-s on the system analysis in regime of network paradigm. It relates also to the conception of model of data postulated by Suppes and van Frassen [8, 9] or at least can be the alternative/complementary representation to the time-series

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analysis. Good example of such analysis are the results of research with the use of recurrent plots and recurrent quantification analysis (RQA) [20-23].

It should be clearly highlighted here that all the above mentioned considerations, i.e. identification of features within the bounds of complex networks, definition of measures for them, classification of networks, activities on the alternative representations of complex networks and interpretative works, are only the fraction of research which are in progress in a range of complex network science. On the other hand, still preliminary research on matching the abstract construction of complex network to the time-space domain have revealed original features of physical systems in both its equilibrium and non-equilibrium states, including e.g. percolation and stochastic resonance phenomena, deterministic and stochastic processes leading to emergence of new states (properties and patterned or non-patterned behaviors) [10, 16-18]. In fact, the network structure serves in these proceedings as the channel for maximization of information exchange [17], which is essential for gathering the knowledge about the object and thus in the context of the main tasks in metrology.

3. COMPLEX NETWORKS IN ENERGY EFFICIENT SMART HOUSE

Exploited by user/-s the energy efficient smart house is the example of complex system embedded in surrounding conditions of environment. Each level of such chain (human being, energy efficient smart house, outer environment) can be independently perceived as the multiscale subject of investigations, each with own singularity in structural organization and in dynamics of processes governing its behavior. When put together, such subsystems are able to produce complex reality of structural and interaction interrelations, which directly can be projected to the abstract domain of complex networks (Fig. 7).

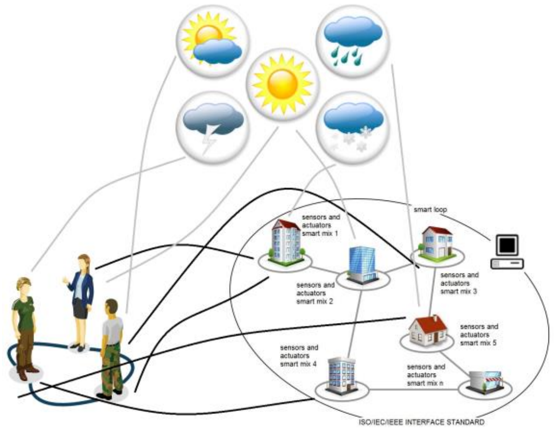

Fig. 7. Complex relations within the multilevel and multiscale environmental object.

Similarly to the case of living organism, where one can move from the subcellular through organ to the whole body level (consisting of numerous organs), the same is at the technical layers of smart home infrastructure exploited (thus influenced) by human being, i.e. physical properties of materials used to manufacturing elements in following technical systems (e.g. heating system, air-condition, electrical grid, information and communication system, etc.) determine their performance at higher levels of organization and finally when they work as an integrity. Further, there are more or less evident environmental factors which determine behavior of inhabitants (e.g. air pollution, atmospheric conditions, planetary and cosmic space configuration, etc.) and also interact with the elements of smart house (e.g. geothermal characteristics, solar irradiance, temperature of air, acidity of water, ground, etc.). All these influence the temporal and long range state of such complex system, working in the network-like complex reality. But in fact, looking forward to the level of smart city conception one should take into consideration the uniqueness of the set configuration of numerous people living in their energy efficient smart homes – for more details see e.g. [19]. Providing the method and tools for monitoring and control of such complex system is a challenge for modern metrology. There are the questions which rises in this circumstance: should the reductionistic or rather integral view be used in this task, what about the actual content of methods and tools suitable for holistic characterization of the real world? The answers will influence the next step in the evolution of contemporary metrology and measurement instrumentation.

4. NETWORK PARADIGM IN METROLOGY

Network science provides some properties which determines the general character of this approach and at the same time respond to the needs of metrology, similarly to the applied mathematics spanned between the world of abstraction and reality. Despite the apparent differences, the emergence and evolution of different network is driven by a common set of fundamental laws and reproducible mechanisms [10, 16-18, 24]. Network science is distinguished, not only by its subject of matter, but also by its methodology and accessible tools. What is more, the domain of complex networks shows inherently the empirical data driven nature, mathematical, interdisciplinary and computational nature. It should be also noticed that in metrology of complex objects, e.g. environmental measurements, apart from the quantities of typical relational nature, there are the attributes of systems which cannot be directly expressed with the use of numbers (e.g. the influence of pain or happiness on behavior and decision of inhavitants, his/her comfort perception, etc.). From the perspective of classical definition of measurement it can be some kind of limitation [1, 25], but regarding the scale of quantities introduced by Stevens [26] network science shows potential to cast light on original inference into the properties of system of units, providing also the consequences for the same issue of complex system measurements. Network science brings also the prolongation of standpoint on the representational problem in metrology. More exactly, network science go between the qualitative experience and related to it the algebraic structures, or in other words network systematics precedes the numerical representation of system attributes – scenario which has been typically applied to raw data in classical measurement. Taking into account the above mentioned, and the role of information in measurement act, directly linked to the issue of model of experimental data [8, 9], one can redefine the conception of measurement according to [8]: measurement of complex systems is an operation that locates an item

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(already classified as in the domain of a given theory – here: complex network theory) in a logical space (provided by the theory to represent a range of possible states or characteristics of such items). Shortly speaking, this definition summarizes one of the opening statements from Tractatus Logico-Philosophicus by L. Wittgenstein: "The facts in logical space are the world".

Complex network is the representation of complex systems, but to be a mapping from the empirical to the numerical relational structure (measurement is a mapping) it needs to have the property of homomorphism or even better the isomorphism. Taking into considerations the facts discussed above two theorem can be postulated.

Theorem 1. The patterns of dependencies in matrix models, dynamical systems and cellular automata are all isomorphic to complex networks.

Theorem 2. In any array of deterministic automata with a finite number of states, the state space forms a complex network.

5. CONCLUSIONS

Network science has emerged as independent field of knowledge of theoretical and experimental meaning. It is strictly connected to the problems of complex systems, which is also the challenge for modern metrology.

The paper points at the common issues within these two domains (network science and metrology), highlights the facts on the inclusion of the former by the later one, and discusses the consequences of such proceeding on measurement of complex systems and metrology, in general. Environmental object of the energy efficient smart house is used for such formulated task. Constituting multilevel and multiscale intricate organization, smart house can provide a bunch of the natural conditions for verification of original contributions, which can represent the universal solutions of urgent problems, especially expressed as the methodological directions for complex system measurement.

When applied to experimental data, complex network provides the knowledge about the state of the object, and in this sense the complex network is a fundamental concept of metrology. In the light of network science, measurement act is an operation that locates an item identified by theory in its logical space. In analogy to the quantum metrology, which introduces the lower bound for measurability (Heisenberg's uncertainty principle), network theory implicates upper bound in the form of free-scale property (free-scale networks) [10].

This conceptual considerations will be supplemented in the next stages by further ontological, epistemic, and technological research, making the measurement in the regime of network paradigm possible and reliable.

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