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Energy Systems of Complex Buildings

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Foreword

Modern complex buildings, such as supermarkets, university campuses, airports, sports and recreation centers, are characterized by more and more complex energy management due to a growing share of distributed energy systems. Thus, energy carriers satisfying the needs of consumers in complex buildings (office rooms in office buildings, refrigerator counters in supermarkets, and so on) are produced in a network of mutually connected energy processes, some of which are of feedback character. These are responsible for the necessity of applying the method of subsequent approximations when the balances of the respective energy carriers are set up separately. The systems approach of energy balancing, which is the basis of the energy analysis both in designing and exploitation, eliminates this disadvantage.

The systems approach applied in this book is generally based on Leontief's "input-output" analysis, supplemented by the characteristic features of energy management of an industrial or municipal system, for instance, the division of the main production of energy carriers into the basic and peak part, or including the by-products of some branches completing the main production of some other branch in the set of balances (e.g., heat from the recovered waste energy supplementing the production of heat in CHP plants). Input–output analysis, as quoted by Leontief, may be usefully applied both in the case of a very large economical system, such as the economy of a whole country, and a single enterprise such as complex buildings. This approach is in every case essentially the same.

This book comprises nine chapters. The first three chapters deal with some selected problems of systems analysis constituting the fundamentals of mathematical modeling of energy systems in complex buildings, both already existing ones and those to be constructed. Chapter 1 presents the idea of a system and its environment. The kinds and features of systems, as well as methods of describing them are presented. Chapter 2 is devoted to large energy systems, drawing the reader's attention to their hierarchical character, which may be applied in optimization. The subject matter of Chapter 3 is the mathematical modeling of large energy systems. Special attention has been paid to input–output analysis and the method of decomposing the global optimization task which makes use of the hierarchical structure of large energy systems.

Chapter 4 serves as an introduction to the application of systems analysis in mathematical modeling of the energy management of complex buildings. Typical complex buildings are described, as well as the ways of supplying them with energy carriers. Special attention is paid to distributed energy systems (particularly small-scale CHP units) and the utilization of renewable energy resources. Chapter 5 stresses the role of the municipal energy sector in the energy system of the country. The supply of heat to complex buildings via district heating networks and ways to control the supply of heat are presented. This chapter also deals with the fundamentals of the cogeneration of heat and electricity, and the idea of "trigeneration", that is a CHP unit integrated with a cooling system. The index PES (Primary Energy Savings) has been analyzed concerning various techniques of cogeneration.

Chapters 6 and 7 are fundamental parts of the book dealing with the systems approach to complex buildings. Chapter 6 contains mathematical models of the balances of direct and cumulative energy consumption, the model of cumulative emissions of noxious substances, and a model of calculating the thermo-ecological costs. The application of the input–output model for systems analysis of rationalizing the energy management of complex buildings is also presented in this chapter. Chapter 7 provides practical examples of applying previously mentioned models, viz., systems analysis of direct and cumulative energy consumption, and cumulative NO_x and CO_2 emissions, as well as calculations and analysis of the thermo-ecological costs. This chapter also contains examples of the application of input–output analysis, assessing the system effects of rationalization of the energy management of complex buildings. A comprehensive example concerns the application of night-cooling ventilation of rooms in the subsystem of consumers. Another example concerns the modernization of the energy subsystem of complex buildings by means of applying a CHP unit. In both these cases system effects concern the decrease in the supply of energy carriers from outside, which are the resultant of all direct and indirect changes taking place in the energy system of complex buildings due to rationalization.

Chapter 8 is devoted to life cycle assessment (LCA) applied in the ecological analysis of complex buildings. It has been stressed that in complex energy systems input–output analysis ought to be used in the life cycle inventory stage. The ecological component of LCA has been presented. This chapter contains an example of the LCA of a typical office building.

Chapter 9 deals with algorithms concerning preliminary design, the aim of which is to choose the optimal structure of the energy management of complex buildings. Systems approach to the procedure of the formation of variants of energy management in complex buildings is presented, as well as Lagrange's decomposition method for choosing the optimal variant. An example of the application of the descriptive model of energy management is given concerning complex buildings, and also an example of an optimization model for choosing the energy management of an industrial-urban complex.

The sequence of the chapters in this book is didactically justified. The first three chapters introduce the reader to systems analysis. The next two chapters acquaint the reader with the energy management of complex buildings. Then it becomes possible to present the mathematical energy-ecological system models of the energy management of complex buildings, and the presented examples permit the reader to become more familiar with the systems approach to the energy management of complex buildings. LCA is an extension of previously presented energy and ecological system models, comprising the full life of complex buildings. The last chapter is largely based on the systems methods presented in the previous chapters.

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Contents

Chapter 1
Introduction into Systems Analysis

Process analysis and systems analysis are two approaches to energy-ecological analysis. Process analysis is a mechanistic approach that dominated the last centuries, although the notion of system has been known since the time of Aristotle. Systems analysis was formally discovered again just before the Second World War by the biologist Ludwig von Bertalanffy, although the methods of systems analysis were already known (e.g., Leontief's "input–output analysis"). System is defined as a set of elements mutually connected and also with the environment, in which the system is situated. A characteristic feature of organized systems is their hierarchical structure. Every system is also characterized by a given degree of coherence and independence. Generally, systems are divided into natural and artificial ones. The features differentiating both these systems are conformability and optimization. The general theory of systems comprises, first of all, the mathematical theory of the system, and secondly system engineering. This book deals with the latter. There are two fundamental methods of describing systems, viz., causal description (input–output analysis) and intentional description (optimization models). The system structure is usually presented either by technological diagrams or structural matrices.

1.1 The Idea of the System and its Environment

Both the conception of system and system approach are as old as European civilization. It is generally accepted that Aristotle's formulation "the whole is more than the sum of its parts" constitutes a first attempt to define the system problem [3]. In researches in the past centuries, however, the mechanistic approach prevailed in which every problem was divided into parts and investigated separately. Thanks to its application so many inventions were made that for many, many years no changes to this approach seemed necessary. In the biological

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sciences, however, it has been observed that in the application of this method, the interconnections between particular parts of an organism are neglected. And, as mentioned, only shortly before the Second World War, the system approach was discovered anew by the biologist Ludwig von Bertallanfy [1], who stated not only that investigations of the parts must be supplemented by investigations of the whole but that there exists a separate discipline which he called theory of systems dealing with the investigations of the whole. For the first time, the general theory of systems was presented in the years 1937–1938 by L. Bertalanffy in his lectures at the University of Chicago [1].

The word "system" comes from Greek and means composition or connection. According to Bertalanffy [1, 3], a system may be defined, as previously stated, as a set of elements connected with each other and also with the environment. More particularly, we may say that a system is an intentionally determined set of elements and relations between these elements and their properties [5]. Such properties are features of the respective objects, the relations being interconnections existing between the respective parts and the whole. Due to these relations, the whole displays properties which do not occur in its parts. The notions "arrangement" and "system" are frequently treated as synonyms. In contradistinctions to arrangements, however, systems may not only be real objects but also abstract ones (e.g., science, education). A real system is arranged in compliance with the physical elements composing the whole, whereas an abstract system is arranged according to its functions, with the properties characterizing the whole. Further considerations in this book concern real systems.

Every system is situated in some environment. Any separation of a concrete system is equivalent to defining the rest as belonging to the environment. Whether a given element belongs to the system or to the environment depends on the subject of investigations, the concrete object, and the aim of investigations. The environment of the system comprises all the objects not belonging to the system, the properties of which affect the system, simultaneously undergoing changes due to the influence of the system. We may distinguish physical, economic, and social environments. The physical environment comprises among others, also other existing systems, the state of technology, and accepted technical standards, as well as the natural environment (geographical situation, raw material resources, climate, flora and fauna), and actual and future experimental and design endeavors. The system cooperates with the environment in the sense that its elements can influence the elements of the environment and vice versa. The interdependence between the respective elements of the system is usually much stronger than between system and environment.

Each system can be divided into subsystems. A subsystem, in which there does not exist any further subsystems of a lower order, is called an element. Each system, again, may be a subsystem belonging to a higher level system (supersystem).

The fundamental system operation comprises the analysis and the synthesis. The former consists in investigations concerning the behavior of the system basing on its structure. The search for the system structure based on the knowledge of its behavior is called synthesis.

1.2 Properties of Systems

The term “system” means “order”. The measure of arrangement in a system is the degree of deviation from the state of thermodynamic equilibrium, defined by Shannon as redundancy [2]:

$$R(\tau) = \frac{S_{\max} - S(\tau)}{S_{\max}}, \tag{1.1}$$

where

$R(\tau)$ redundancy at the moment τ,

$S(\tau)$ entropy of the system at the moment τ,

$S_{\max}$ entropy of the system at the equilibrium state.

In the case of an ideally arranged (perfectly organized) system, $R = 1$. A completely disorganized (chaotic) system corresponds to $R = 0$. A factor favoring the arrangement of the system is a control. Systems arranged according to the defined functions of the respective elements are called organized systems [2].

A characteristic feature of organized systems is their hierarchical structure. This property consists in the fact that the respective elements of the system are systems of a lower order (subsystems), and the given system being considered constitutes a subsystem of a higher order (supersystem). This property permits the system to be divided into subsystems. In each system with a hierarchical structure, we can distinguish elements of the highest (central) level, which in the given system have no superior elements, as well as elements of the lowest level (zero level) without any subordinate elements. Between the central level and zero level, there may occur intermediate levels whose elements are simultaneously subordinated to elements of the higher level and superior to the elements of a lower level. The complexity of hierarchical structures is a special feature of large energy systems.

The property called centralization is connected with systems that have a hierarchical structure. This process consists in incrementing the coefficients of interdependence in one of the subsystems. Thus, slight changes in the subsystem involve considerable changes in the whole system. The subsystem which plays a deciding role in the operation of the entire system is called the controlling part of the system. Centralization is a property varying in time and resulting in an increase (progressive centralization) or reduction (progressive decentralization) of the controlling function.

Every system is characterized by a given degree of coherence which consists in a connection of the respective elements so that a change in any one of them involves changes in the other elements and vice versa; a change in any arbitrary element depends on all the other elements of the system.

Independence is the opposite of coherence. In such a case, no connection exists between the elements of the system, so that a change in any one of the elements does not lead to changes in any other elements of the system. In this case, changes in the system are the sum of individual changes in the elements. Interactions are then equal to zero. In the case of an absolute independence of the elements, there is no system. It is rather a set of functionally mutually independent elements.

Coherence and independence are extreme cases of the same property of the system. Both these quantities may occur in various degrees. The degree of coherence and independence changes in time. The transition of a coherent system to an independent one is called progressive division. Progressive integration is characterized by the intensification of already existing connections between the elements of the system and increasing number of connections or the inclusion of new elements and connections into the system, as a result of which the coherence increases. In contradistinction to progressive division, progressive integration involves an increase in the organization of the system.

Other properties of the systems worth mentioning are adaptability, stability, and equifinality. Adaptability is the property of the system permitting to react to changes in the state of the system and in the state of the environment favoring its further existence. The stability of the system is the ability to decrease automatically the effect of disturbances up to their complete elimination. Equifinality is a property which permits the system to achieve some given aim starting from various preliminary states.

The intelligence of the system is a property that permits the system to understand why some given state has come into being and the consequences of changes in the coupling and the utilization of these perceptions in order to educate the system. This education is a process of changing the structure, the organization, or properties of the adaptive system caused by iterative stimuli, in order to achieve a more effective behavior of the system.

1.3 Classification of Systems and their Characteristics

In Sect. 1.1, we drew attention to the division of systems into real and abstract ones. Real systems may be subdivided into small and large systems according to the number of their elements. The number of internal connections between the elements of the system decides about its complexity, viz., [5]:

a. simple system with the least possible number of connections $l = n - 1$, where n denotes the number of elements,
b. complex system with a number of connections within the range $n - 1 < l < n(n - 1)$,
c. particularly complex systems with a number of connections $l > n(n - 1)$.

From the viewpoint of connections with the environment we can distinguish:

a. open systems exchanging substance, energy, and information,

b. closed systems characterized by a lack of exchange of the substance; in this case, energy is exchanged by means of such forms of transportation which do not required the substance (heat, mechanical, or electrical work); also information is exchanged with the environment,
c. separate systems exchanging neither substance nor energy nor information.

As far as the variability of the states of the systems in time is concerned, we can distinguish static and dynamic systems. Dynamic systems display structural or functional structures changing in time. Dynamic systems may also be divided into deterministic and probabilistic ones. We have to do with a deterministic system when the knowledge of the values of the respective variables in any given moment permits the state of the system to be determined explicitly at any later moment. In the case of a probabilistic system, its new state can be predicted only with some probability.

From the viewpoint of human activities in constructing the systems, they may be divided into natural and artificial ones. Natural systems are encountered in nature. Their existence depends particularly on their ability to adaptation, consisting in the fact that the system adapts itself to changes in the environment in a way most favorable for its further operation.

Natural (biological) systems are characterized by the so-called homeostasis. This is the ability of the system to keep certain quantities within ranges conditioned by the possibility of its adaptation in spite of even considerable changes in external conditions [5]. The phenomenon of homeostasis occurs thanks to mechanisms of self-regulation, connected with the application of the feedback. In natural systems, the number of feedbacks is considerable. Thus, they are ultrastable systems. The system is ultrastable if after exceeding one feedback loop a next loop with another range of operation is included.

Artificial systems, dealt with further on, are systems constructed by humans. Some features are common to both groups of systems, but there are differences of essential meaning. Coherence and independence are common features of natural and artificial systems. Centralization and adaptability are more characteristic of natural systems. In artificial systems, feedback mechanisms are either not active or too weak. Therefore, artificial systems are unstable. Artificial systems display other properties such as conformability and optimization, which do not occur in natural systems [2, 5]. Conformability consists in a system with a structure that matches the environment. Optimization, on the other hand, consists in ensuring the best possible adaptation of the system to the environment. This issue does not concern natural systems, because during their long period of development, they can adapt themselves to the environment in the best possible way.

An essential difference between natural and artificial systems is their reliability, which determines the probability with which the system will display in some given process the required and previously determined behavior. Reliability comprises freedom from failure, durability, and the possibility of repair. Freedom from failure is the ability of the system or element to keep up its efficiency in given conditions of functioning and in a defined interval of time. Durability is the ability

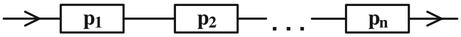

Fig. 1.1 Series structure of system

of the system or element to be used under given conditions and at an adequate level of service. The possibility of being repaired consists in preventing, detecting, and removing damages which may occur incidentally (breakdown), or may be due to aging of the system or element.

In contradistinction to artificial systems, natural systems are characterized by a high reliability due to the fact that the respective subsystems are composed of a large number of reserve elements. Artificial systems are constructed economically without an excess of elements. Their structure is usually, therefore, a series structure. For this reason, the failure of any element involves the breakdown of the whole system.

The reliability of a system composed of elements connected in series (Fig. 1.1) results from the assumption of mutual independence of the respective elements:

$$p = \prod_{i=1}^{n} p_i, \tag{1.2}$$

where

p probability of lack of failure in a system (reliability of the system),
p_i probability of lack of failure in the ith element (reliability of the ith element),
n number of elements in the system

As can be seen in Eq. 1.2, the reliability of the system decreases with the growing number of serially connected elements. Such a conclusion is justified when we assume that in any element "i" $p_i = 0$ is not valid and that all the elements $p_i = 1$ do not occur simultaneously. An increase in reliability of any element involves an increase in the reliability of the whole system.

The reliability of an artificial system can be effectively improved by introducing an adequate number of parallels by connected reserve elements (Fig. 1.2). In the case of (m − 1), reserve elements the reliability of the ith element resulting from the equation [5]:

$$p_i = 1 - \prod_{j=1}^{m_i} (1 - p_{ij}), \tag{1.3}$$

where

p_{ij} reliability of the jth element, which is a reserve of ith element,
m_i number of all elements with the same function (base element and reserve elements) in the ith element of the system.

The reliability of the whole system composed of n elements connected in a series, each of them having $(m_i - 1)$ reserve elements, may be expressed by equation [5]:

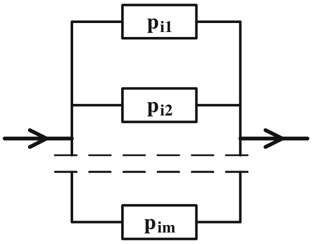

Fig. 1.2 Parallel structure of the system

$$p = \prod_{i=1}^{n} \left[1 - \prod_{j=1}^{m_i} \left(1 - p_{ij} \right) \right]. \tag{1.4}$$

An increase in the reliability of each element and in the number of parallelly connected elements improves the reliability of the system.

1.4 An Excerpt of the General Theory of Systems

The general theory of systems is a logical–mathematical domain, the aim of which is to formulate and derive principles applied in various kinds of systems. The general theory of systems, originally connected with biology, is the result of attempts to apply thermodynamics in biology. Bertalanffy stressed the fact that Onsager's thermodynamic of irreversible processes is an example of the systems approach [1]. An essential feature of the theory of systems is its generality and abstractness, as well as the fact that it investigates the features of systems and not their physical phenomena by means of mathematical methods.

The fundamental method of the general theory of systems consists in assigning the isomorphism of laws concerning various domains of science. In the general theory of systems, isomorphism is deduced from the analogy of physical phenomena (e.g., heat conduction and electric current). These analogies may also concern absolutely different phenomena, e.g., the flow of liquids and interbranch flow according to Leontief's "input–output analysis" [4]. Isomorphism occurring between two systems is to be understood as a mutually explicit correspondence between the elements of one system and some other system, and the existence of the same relations between the corresponding elements of both systems. Two concrete systems may be determined as mutually isomorphic if both of them can be presented by the same mathematical model. Isomorphism between two mathematical models permits conclusions to be drawn about the isomorphism between two concrete systems represented by the given mathematical systems. The similarity of algebraic equations or differential equations is a kind of mathematical isomorphism. An example of two isomorphic concrete systems is first of all the phenomenon of steady-state heat conduction in solid bodies without internal sources of heat and with a constant thermal conductivity, and secondly, the phenomenon of a steady-state field of the electric potential in a conductor with a constant electric conductivity. The respective differential equations, being mathematical models of the considered systems, take the form:

$$\nabla^2 T = 0, \tag{1.5}$$

$$\nabla^2 U = 0, \tag{1.6}$$

where
T temperature,
U electric potential,
∇^2 Laplace operator.

In this example the mathematical models are isomorphic. Thus, concrete systems presented by these models are also isomorphic. There is an analogy between temperature and the electric potential, thermal conductivity and electric conductivity, between thermal resistance and electric resistance, thermal capacity and capacitance, and the heat flux and current intensity. Electrical analog models were formerly used to solve differential equations of heat conduction in the case of bodies with a complex geometry.

The general theory of systems distinguished the following domains of investigations:

- mathematical theory of systems,
- system engineering,
- philosophy of systems.

The mathematical theory of systems comprises the general theory of systems in its narrower meaning, cybernetics, control theory, theory of information, set theory, graph theory, game theory, and simulation theory. Based on set theory, the system S may be defined as follows [3]:

$$S \subset \times \{ V_i : i \in I \}, \tag{1.7}$$

where
V_i element of the system,
I set of indices.

The relation defined by Eq. 1.7 denotes that system S is a subset of the Cartesian product on the elements V_i of the system.

If I is the finite set, we get [3]:

$$S \subset V_1 \times V_2 \times \cdots \times V_n. \tag{1.8}$$

The Cartesian product $V_1 \times V_2 \times \cdots \times V_\mathrm{n}$ is a set of all the vectors $[v_1, v_2, \ldots v_\mathrm{n}]$, so that $v_\mathrm{i} \in \mathrm{V_i}$ for $i = 1, 2, \ldots, n$.