Planning and management of urban environment using the models of degradation theory

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Abstract. Urban systems are the most complex multi-level objects. The construction and design of such systems is preceded by their analysis and deep study. The article considers the issue of long-term planning of urban systems. The planning is based on the forecast of evaluation of buildings, structures and other urban systems durability. The longevity forecast is proposed to be implemented on the basis of models of degradation theory. The theory of degradation is developed as a general energy method for estimating the longevity of objects. It is based on the law of conservation of energy. To analyze the longevity of urban environment, it is proposed to adopt the simplest model of theory of degradation. The proposed work provides an explanation for the description of proposed model. The urban environment is divided into a number of simpler systems. The more the degree of system separation into simpler ones, the more accurately one can describe the behavior of the entire system in time. Each simple system is described by the simplest model of degradation theory. The general behavior of the system is understood as a simple sum of individual degradation models. A feature of the proposed theory is that the simplest model can describe the entire system or the sum of its individual parts at once. The model makes it possible to consider the issue of equalizing the longevity of individual systems. The analysis of durability of a multicompartment building is taken as an example. In terms of analyzing the given example, individual stages of systems operation, that are still subject to discussion, are identified.

1. Introduction

Urban environment is a complex multi-level object. Such an object includes multilevel development, ecological systems, energy systems, transport and intellectual systems. All this structure is in constant movement in time and space. Each system and all systems together after their occurrence begin to decay, degrade and gradually die off. Some systems are systematically restored or destroyed. Some structures can collapse from unforeseen influences. New systems, structures and their connections are emerging. It is necessary to manage and plan the ongoing processes. To do this, it is necessary to be able to assess the longevity of an individual building, a separate system, and also the whole city, urban systems.
Each planning and management should develop through modeling and design. Therefore, in recent years, the designing is understood not as a static process of assessing strength and deformability, but also as a process of durability assessing. The term "durability" is now often replaced by the term "service life". The planning process includes the renovation process, which can also be both natural and systematic. When renovating, not only the built-up area itself is affected, but all adjacent territories in greater or lesser extent (also depending on distance) [1].

2. Models of durability of buildings and structures

A lot of scientific works are devoted to questions of practical and philosophical longevity. In work [2] modern approaches to the evaluation of technical durability are described in sufficient details. In particular, it is proposed to introduce into the design standards a calculation based on a new limit state – durability.

Models of durability as a whole can be divided into general and differential (simplified and detailed) [2, 3]. A general degradation model is proposed to be written in the following way [4].

$$\mu(D) = D(x_1; x_2; \ldots x_n; t).$$

$M(D)$ – degradation average; $x_1; x_2; \ldots x_n$ – models of object and environment parameters, $t$ – age.

Such a record makes it possible to use a mathematical model for a multidimensional system both in the form of a general model and in the form of a cumulative integrated model.

The models of each object parameter are usually considered separately. Thus, one of the most well-known models for evaluating the durability of a reinforced concrete structure operating in an aggressive environment is the model proposed by Tuuti [5]. The crack growth model, for example, can be used depending on the influence of various factors and finally determines the longevity as the element-wise effect of different factors on the growth of the critical crack [6].

Several possible forms of models can be considered for one parameter, the compatibility criterion of which is the substitution of the coefficients, which subsequently lead to similar results [7].

A distinction is made between planning using normalized characteristics or by results of field surveys. The object is divided into parts and then, summing the longevity of individual parts, the overall longevity of the object is determined [8]. Physical wear according to BCH [9] is determined by summing the average-weighted wear of individual sections of a structure or building at a replacement or estimated cost. Figure 1 shows some known models of physical deterioration of buildings and structures. Well-known graphs and dependencies are obtained empirically and are based on observation experiments and estimating the costs of routine repairs. The capital repair expenditures can extend the service life of structures. Figure 1b shows the option of reducing the physical wear of a building with the subsequent extension of its service life. It can be seen from the figures that the physical wear of different objects is described by approximately the same physical laws. However, some discrepancies in the behavior of objects are revealed, especially at the beginning of their life cycles. The graphs show a significant zone of stable operation. In general, the shape of the graphs reflects the approach to finding the criterion of durability and a purely practical approach to repair and restoration of structures.

3. Approaches of degradation theory to the assessment of physical wear of urban environment

The theory of degradation is based on a general energy approach to the interaction of environmental objects [11]. Theory presupposes that each object has its own form of energy. The form of energy is made up of individual elementary forms. Based on the assumption of the initial form of energy, a model is constructed for the interaction of an object with the environment. The final shape of the object energy is established after comparing the obtained model with the physical object of construction. The basis of the model is the energy potential of the object. Potentials of energy are of three types: constant, ascending and descending. The ascending potentials, built in the direction of their complication, look like this:

$$B'_0 = B_0(L - t)/t; B'_1 = B_1(L^2 - t^2)/2Lt; B'_2 = B_2(L^3 - t^3)/2L^2 t \ldots.$$  

(2)
In the given expression $B_1^*$ is a simple potential of an object; $B_1$ acceleration of the object’s energy in the moment of death; $L$ life duration of the object; $t$ current time.

Figure 1. Models of physical deterioration of buildings and structures

The total potential of an object is obtained by summing the potentials of energies. A feature of simple potentials is that for simple potentials a time potential is allocated that does not depend on the energy of the object. In this case it is possible to study the behavior of objects in time, regardless of their cost and volume.

Analysis of the behavior of potentials has also revealed some specific features of energy behavior over time. One of the main features is the existence of the initial zone of "elastic work" of the material (designation a). The zone separates the operation of the object without the occurrence of additional defects. "Elastic zone" characterizes the initial defects of the object. The smaller the "elastic zone" the better the object. In complex objects, such as buildings and structures, the initial defective zone is greater than in individual components of the object.

The simplest form of potential (the first dependence in (2)) is the average of all the ascending and descending forms of potential. Therefore, it can be used to predict the behavior of an object [11]. The actual wear of an object in comparison with the simplest form will be somewhat more or less intensive, but the tendency of its behavior in time will remain.

As already noted in the simple form, the potential does not depend on the value of energy. Therefore, here we see the interrelation of all objects in time, since in the first simple form the
behavior of all objects is described by a single curve. For a compound object, the difference will be only in the multipliers used for each component of the object.

4. Approach to the analysis of physical wear of an object

A simple stable interaction potential is taken as the basis of the analysis [12, 13]. It is the basis to construct the dependence of work of object A in time:

\[
A = B^*(L \cdot t \cdot \ln t/a - 0,5(t^2 - a^2) - (L - a)(t - a))
\]  

(3)

Figure 2. Graphs of potential B and work A of structure

For clarity, Figure 2 shows graphs of the value of B for a lifetime of L = 100 years and A for a lifetime of L = 100, 80, 60, 40 and 20 years. The graphs are constructed with the duration of defect-free operation of an object for 4 years. That means that all defects occurring in the object within 4 years will have less influence on the object than existing defects. The energy characteristic B * is taken equal to one. Therefore, the graphs shown characterize the behavior of the object only in time.
Fig. 2 shows the work schedule of the object with a lifetime of $L = 100$ and a duration of operation without defects $= 10$ years. That means that the number of initial defects in the object is large (compared to $a = 4$) and is compensated only after 10 years of operation. The decrease in the life span of the object due to initial defects was 30%. This explains the significant reduction in cost and duration of the object operation due to poor-quality of construction. In a complex facility, which is a building, the initial increased number of defects is more likely than in a simple product. Therefore, the reduction of initial defects is so important in the construction of buildings.

The graphs highlight the indicative time values. They are all interconnected. This is the time corresponding to the following values:

- $L$ – the lifetime of an object, determined by the comfort and safety of operation, in the present understanding means 100 % physical wear of the object;
- $a$ – the time when the effect of initial defects of the object on its durability exceeds the influence of current defects arising during the operation of the object;
- $Tr$ – the time when the object fails to resist external influences;
- $Tp$ – the time of complete destruction of the object.

The indicative points are shown only for the lifetime of the object of 100 years.

As we can see from the figure, the service life of a product 0.6 $L$ is much less than the duration of its destruction. That means the need for additional costs for demolishing or renovating the object.

5. Example of physical wear analysis of an object basing on the theory of degradation

As a subject of research, a 16-floor apartment house in Chelyabinsk was chosen. The analysis of cost formation of its construction was carried out. The data was collected on the basis of estimates for the construction with the prices as of 2000, provided by OJSC "Design Institute for Planning and Development of Cities and Settlements" Magnitogorskrazhdanproekt". To evaluate the physical wear in value terms, a decision was made to group the structures according to their minimum useful life for residential buildings [9].

The structural elements of the frame house were divided into five groups according to the period of operation according to the table 1.

| Name                                                                 | Cost th. Rub. |
|----------------------------------------------------------------------|--------------|
| Group 1 (100 years) – reinforced concrete structures                  | 10560.451    |
| Group 2 (80 years) – external walls                                  | 5856.531     |
| Group 3 (60 years) – airbricks, staircases, ventilation shafts       | 889.183      |
| Group 4 (40 years) – openings, floors, interior finishing, partition walls, windows, stained-glass windows, doors | 15602        |
| Group 5 (20 years) – exterior finishing, automation, low-voltage devices, heating, ventilation, water supply and sewerage, electric lighting, roofing, interior finishing | 12178        |
| Total                                                                | 45085        |

For the analysis in the above dependence (3), the energy characteristic of object B * receives the dimension "ruble" with the use of a conversion coefficient for the numerical axis. The actual initial defectiveness $a$ can be determined by a special act upon acceptance of the object into operation.

The total cost of structural elements will be different from the cost of an apartment house construction. That has to do with the fact that during assessment of physical depreciation, only the direct costs of structure erection are taken into account, that is, the cost of materials without taking into account labor costs and other additional works. The data in the table are used to construct the graphs shown in Figure 3. The graphs are plotted on the basis of graphs A according to Figure 2, where the energy characteristic of object B * is selected according to the table in accordance with the scale of prices.
6. Conclusion

It is clear from the schedule that after forty years of operation the wear of a building starts to increase rapidly. Slowdown is projected at 80 years of operation. At this level a building's durability is predicted [14, 15]. The maximum wear of a building is projected after 120 years. The greatest impact on the wear of buildings is provided by systems with a short service life and relatively cheap. Therefore, the restoration of small systems of group 5 (shown in dotted lines in the figure) after forty years of operation led to an increase in the service life of the entire building for 30 years. The recovery of systems of Group 6 resulted in an additional increase in the service life by 5 years. Changing of individual components makes it possible to optimize the building operation.

Figure 3. Operation schedule of a complex object

The cumulative schedule shows the physical wear of a complex object. Within the existing approach, when assessing the physical wear of a building, a linear graph of physical wear can be taken into account.

The upper diagram in Figure 2 can be taken as a simple generalized depreciation diagram of an object.

The considerable value of a falling line of physical wear shows that the existing structures of the building in question (heavy reinforced concrete) significantly increase the cost of construction and unreasonably increase the service life of the building. In fact, some reinforced concrete structures will have even longer service life.

The existing approach to assessing the physical wear of buildings has a more economic approach than a technical one.

In fact, this article demonstrates the simplest approach to assessing the physical wear of an object. Only the diagram of object operation was considered (as is customary with the existing approach). When assessing the wear, it is necessary to consider the whole complex of diagrams, starting with the energy distribution diagram in time, the distribution diagram of potential, the power and operation distribution diagrams of the object.

At first, it is supposed to analyze the degradation behavior of the environment using models of degradation theory. With the accumulation of experience, the model of degradation theory can be used in planning and design of urban systems.
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