AN INTEGRATED MODEL OF PLANNING PROCESSES FOR BUILDING DEVALUATION AND RENOVATION

A novel integrated mathematical model for the devaluation of buildings with time and the restoration of their value through renovation is presented. The traditional approach of treating individual building components is extended to complete buildings and groups of buildings through the introduction of classified sets and renovation groups of building components. The time history of the accumulated renovation costs is determined. It is suitable for rational planning of the renovation strategy and of an economic balance between resources assigned to new construction and resources used for the renovation of buildings.

Key words: building devaluation, integrated mathematical model, renovation process, rational planning.

Valuation of buildings is essential because buildings are subject to unavoidable physical and chemical processes which decrease their value with time. This devaluation is counteracted by renovation which restores the value of the building. Civil engineers must achieve a proper balance between the devaluation and renovation processes. The aim is to limit the deterioration of buildings with time and to balance the resources which are needed for new construction, maintenance and renovation.

The development of a rational renovation policy requires a model of the process of building devaluation and restoration. This paper presents quantitative methods for the modeling of the devaluation and renovation of individual building components as well as complete buildings and groups of buildings. The methods are implemented in a model which can be used to determine suitable points in time for the renovation of groups of components and for the prediction of the accumulated initial and renovation costs during life span of the building.

The integrated model of the building devaluation and renovation planning process is developed in four stages which are described below.

In the first stage devaluation diagrams for single components are constructed with the method of Schroeder [1]. The normalized value $v$ of the component at age $t_c$ is the ratio $v$ of its value $v_c$ at age $t_c$ to its new value $v_{c0}$. The normalized age $t$ of the component is the ratio of its current age $t_c$ to the age $t_{c,null}$ at which its value becomes null:

$$ v = \frac{v_c}{v_{c0}} \quad (1) $$

$$ t = \frac{t_c}{t_{c,null}} \quad (2) $$

Observation of buildings [1, 2] has led to a devaluation function expressing the normalized value of a component in terms of the normalized age and a devaluation rate $\alpha$ whose value depends on the type of the component and on its environment in the building:

$$ v(t) = 1 - t^4 \quad (3) $$

The smallest value $v_{life}$ of a component at which it can still be renovated is called its critical value. The normalized age $t_{life}$ of a component with critical value is called its normalized life span. The normalized life span follows from expression (3):

$$ t_{life} = \sqrt[4]{1 - v_{life}} \quad (4) $$

Because the devaluation process of a new component can differ from that in the later part of its life span the two-phase devaluation diagram of figure 1 is introduced. Phase 1
reflects the special initial loss of value due to such effects as initial cracking, settlement and wear. Phase 2 reflects the gradual aging of the component due to chemical and physical processes as well as normal wear and tear.

![Diagram showing two-phase devaluation](image)

**Fig. 1. Two-phase devaluation diagram**

The phase transition point lies on the diagonal of the diagram. The devaluation rate $\alpha_1$ in phase 1 relates normalized value $v$ and time $t$ as follows:

$$v = 1 - (1 - v_1) \left( \frac{t}{t_1} \right)^{\alpha_1} \quad 0 \leq t \leq t_1$$  \hspace{1cm} (5)

$$t = t_1 \sqrt{\frac{1 - v}{1 - v_1}} \quad v_1 \leq v \leq 1$$  \hspace{1cm} (6)

The devaluation rate $\alpha_2$ in phase 2 relates normalized value $v$ and time $t$ as follows:

$$v = v_1 - (v_1 - v_{life}) \left( \frac{t - t_1}{t_{life} - t_1} \right)^{\alpha_2} \quad t_1 \leq t \leq 1$$  \hspace{1cm} (7)

$$t = t_1 + (t_{life} - t_1) \sqrt{\frac{v_1 - v}{v_1 - v_{life}}} \quad 0 \leq v \leq v_1$$  \hspace{1cm} (8)

The normalized life span $t_{life}$ for a given critical value follows from expression (8) by setting $v = 0$ for $t = 1$.

In the second stage the devaluation diagram of a complete building is constructed. The building is defined as a set of building components which is decomposed into classified sets, each of which contains building components of exactly one class, for example class window. Two difficulties must be overcome in this approach:

- The normalized values of different components cannot be added because the absolute values of these components differ.
- Components with equal normalized age have different absolute ages because their life spans differ. If two components with different life spans are to be regarded at the same point in calendar time, they must be regarded at different normalized times.

In order to make the devaluation diagrams of components with different life spans comparable, the devaluation functions (5) to (8) are transformed to calendar time by substituting the normalized time from expression (2). The equations for phase 1 are:

$$v = 1 - (1 - v_1) \left( \frac{t}{t_{c1}} \right)^{\alpha_1} \quad 0 \leq t_{c1} \leq t_1$$  \hspace{1cm} (9)

$$t_{c1} = t_1 \sqrt{\frac{1 - v}{1 - v_1}} \quad v_1 \leq v \leq 1$$  \hspace{1cm} (10)
The equations for phase 2 are:

\[
v = v_1 - (v_1 - v_{\text{life}}) \frac{t_c - t_{\text{cl}}}{t_{\text{cl,life}} - t_{\text{cl}}} \quad t_{\text{cl}} \leq t_c \leq t_{c,\text{null}}
\]

\[
t_c = t_{\text{cl}} + (t_{\text{cl,life}} - t_{\text{cl}}) \sqrt{\frac{v_1 - v}{v_1 - v_{\text{life}}}} \quad 0 \leq v \leq v_1
\]

The devaluation of a building is related to the devaluation of its components by considering the building as a component set B which is decomposed into n classified component sets \(\{S_1, \ldots, S_n\}\):

\[
B = S_1 \cup S_2 \cup \ldots \cup S_n \quad i \neq k \in \{1, \ldots, n\} \Rightarrow S_i \cap S_k = 0
\]

Because it is very difficult to determine the absolute value of building components, their value is derived indirectly. The initial value \(v_{c0}(S_i)\) of each classified set \(S_i\) is expressed as a fraction of the total building value \(v_{c0}(B)\). This fraction is called the significance \(g_i\) of the set and is estimated statistically. The sum of the significances of the classified sets of a building is 1.

\[
v_{c0}(S_i) = g_i \cdot v_{c0}(B)
\]

\[
\sum_{i=1}^{n} g_i = 1
\]

Let there be \(n_i\) components in set \(S_i\). A weight \(w_{ik}\) is assigned to each component \(h_{ik}\) of the set to reflect its relative value. The initial value \(v_{c0}(h_{ik})\) of the component is expressed as a fraction \(z_{ik}\) of the value of the building. This fraction is called the participation factor of component \(h_{ik}\):

\[
v_{c0}(h_{ik}) = z_{ik} \cdot v_{c0}(B) \quad \text{with} \quad z_{ik} = \frac{g_i \cdot w_{ik}}{\sum_{k=1}^{n} w_{ik}}
\]

The normalized value \(v_{ik}\) of component \(h_{ik}\) at age \(t_c\) is computed with expressions (9) or (11). The absolute value \(v_c(h_{ik})\) of the component follows from expression (16):

\[
v_c(h_{ik}) = v_{ik} \cdot v_{c0}(h_{ik}) = v_{ik} \cdot z_{ik} \cdot v_{c0}(B)
\]

The model is based on the hypothesis that the absolute value \(v_c(B)\) of the building equals the sum of the absolute values of its components:

\[
v_c(B) = \sum_{i=1}^{n} \sum_{k=1}^{n_i} v_c(h_{ik}) = v_{c0}(B) \sum_{i=1}^{n} \sum_{k=1}^{n_i} v_{ik} \cdot z_{ik}
\]

The normalized value \(v_c(B)\) of the building at time \(t_c\) follows from (18):

\[
v_c(B) = \frac{v_c(B)}{v_{c0}(B)} = \frac{\sum_{i=1}^{n} \sum_{k=1}^{n_i} v_{ik} \cdot z_{ik}}{\sum_{i=1}^{n} \sum_{k=1}^{n_i} v_{ik}}
\]

In the third stage a theory for the renovation of building components is developed. Any activity which increases the normalized value of a building component is called a renovation. The value \(v_c\) of the component immediately before renovation is called the trigger value for the renovation. The value \(v_p \leq 1\) of the component immediately after renovation is called the level of renovation.

The effort required to perform a renovation is called the renovation cost. The ratio between the normalized renovation cost \(s\) and the improvement \(v_p - v_c\) in the value of the component is called the renovation cost ratio \(f\):

\[
s = f(v_p - v_c)
\]

Cost ratio \(f\) is related to the trigger value \(v_c\) with the renovation sensitivity \(b\):

\[
f = 1 + \frac{v_c}{1 - v_p^b}
\]
The ratio of the renovation cost $s$ to the trigger time $t_{cs}$ is called the renovation cost ratio $q_{cs}$. For trigger times in phase 2 of the devaluation diagram the renovation cost ratio follows from expressions (12) and (20):

$$q_{cs} = \frac{s}{t_{cs}} = \frac{(v_p - v_1) \left(1 + \frac{v_1 - v_p}{1 - v_p}\right)}{t_{cl} + (t_{c,life} - t_{cl}) \alpha v_1 \frac{v_1 - v_1}{v_1 - v_{life}}} \quad 0 \leq v_1 \leq v_1$$

Trigger value $v_1$ is expressed as a function of calendar time $t_c$ with equation (11) and substituted into expression (22) to obtain $q_{cs}$ as a function of calendar time and the optimal trigger time for electrical equipment as shown in figure 2 ($\alpha = 5, b = 5$).

Expressions (9) to (12) describe the initial devaluation of a component before the first renovation. The devaluation diagram for the time following the first renovation is obtained by a time shift $t_{c,shift}$ of the initial devaluation curve on the time axis as shown in figure 3. The time shift $t_{c,shift}$ is chosen so that the shifted devaluation curve passes through point $(t_{cs}, v_1)$. The time increment from time shift $t_{c,shift}$ to trigger time $t_{cs}$ is the calendar time $t_{cp}$ corresponding to the renovation level $v_1$, which is computed with equation (12) in phase 2 of the initial devaluation curve.

$$t_{c,shift} = t_{cs} - t_{cp}$$

The following equations describe phase 1 of the shifted devaluation curve:

$$v = 1 - (1 - v_1) \left(1 - \frac{t_{c,shift}}{t_{cl}}\right)^{\alpha_1} \quad t_{c,shift} \leq t_c \leq t_{c,shift} + t_{cl} \quad (24)$$

$$t_c = t_{c,shift} + t_{cl} \frac{1 - v}{1 - v_1} \quad v_1 \leq v \leq 1$$

The equations for phase 2 of the shifted curve are:
In the fourth stage the renovation of a complete building is modeled. The building components of set B are arranged in renovation groups which are independent of the classification sets. All components of a renovation group $G_m$ are renovated at the same time.

A rule is formulated for the trigger time of the group, for example:

The renovation of the group is triggered if any one of the components of the group reaches its trigger value $v_s$.

Some of the components of the group are marked as essential components. The renovation of the group is triggered if any essential component of the group reaches its trigger value $v_s$. If an unessential component reaches a negative value its value is set to null and the renovation of the group is not triggered.

The time shift for the components of the group is computed in two steps. In the first step the trigger time is computed with equation (9) or (11) for each essential component of the group. The smallest of these trigger times is chosen as the trigger time of the group and is denoted by $t_{c,min}$. In the second step the time shift parameter is computed for each component of the group. The value $v_{s,min}$ of the component at time is given by equation (9) or (11). The time $t_c$ corresponding to the renovation level $v_p$ of the component is given by equation (10) or (12). The time shift for the component is computed with equation (23).

In order to compute the devaluation diagram of a renovation group $G_m$ with $n_{em}$ components $g_{me}$ from time 0 to time $t_{c,min}$ the time span is subdivided with time stations $t_i=0, dt_i, …, t_{c,min}$ into equal time intervals $dt_i$. The normalized value $v(G_m, t_i)$ of $G_m$ at a time station $t_i$ equals the sum of the normalized values $v_{me}(t_i)$ of the components at the time station, multiplied with their participation factors $z_{me}$:

$$v(G_m, t_i) = \sum_{e=1}^{n_{em}} z_{me} v_{me}(t_i)$$  \hfill (28)

The devaluation diagram for the time span between the first and the second renovation is computed in a similar manner, except that equations (24) to (27) which contain the time shift replace equations (9) to (12). Figure 4 shows the devaluation diagram of a renovation group after 4 renovations.

The devaluation diagram for a building is related to the renovation diagrams for renovation groups by decomposing the component set B of the building into $n_g$ renovation groups $G_{mg}$.
The normalized value $v(B, t_c)$ of the building at time $t_c$ equals the sum of the normalized values $v(G_m, t_c)$ of the renovation groups at time $t_c$:

$$v(B, t_c) = \sum_{m=1}^{n} v(G_m, t_c)$$

(30)

The values in the devaluation diagrams of different renovation groups are not computed at the same points in time and therefore cannot be added directly to yield a value of the building. The time stations for the renovation groups are therefore modified as follows. Let $t_{cs, \text{last}}$ be the last time a group was renovated, and $t_{cs, \text{next}}$ the time when the next group is renovated. The time span from $t_{cs, \text{last}}$ to $t_{cs, \text{next}}$ is subdivided with time stations $t_i = t_{cs, \text{last}} + i \cdot dt_c$, into equal time intervals $dt_c$. The normalized value $v(B, t_c)$ at a time station $t_i$ equals the sum of the normalized values $v(G_m, t_c)$ of the renovation groups at the time station. The devaluation diagram for a building is similar to the diagram for a renovation group in figure 4.

The renovation cost for a renovation group or for the building is presented in an accumulated renovation cost diagram. The diagram for group $G_m$ shows the variation of the accumulated group renovation cost with age. Let the group be renovated at times $t_{cs, \text{min}}$, $t_{cs, \text{min}}$, $t_{cs, \text{min}}$, $t_{cs, \text{min}}$, $t_{cs, \text{min}}$, $t_{cs, \text{min}}$. The renovation cost $s^{(j)}(G_m)$ at time $t_{cs, \text{min}}$ is computed as the sum of the renovation costs $s^{(j)}_c(G_m)$ of the components $c_m$ of $G_m$, each multiplied with its participation factor $z_{me}$:

$$s^{(j)}(G_m) = \sum_{c=1}^{n} z_{me} s^{(j)}_c$$

(31)

The costs of the renovations at the time stations are added to yield the accumulated cost diagram of the group in figure 5. The cost diagram for a building is the sum of the cost diagrams of the renovation groups of the building.

**Conclusions**

The integrated model of planning processes for the devaluation and renovation of buildings which is presented in this paper extends existing concepts for individual building components to novel concepts for complete buildings or groups of buildings. The advances are based on the new concepts of classified sets and renovation groups. The input parameters for the algorithms have been chosen in such a way that suitable values can be determined in engineering practice. It has been shown with a pilot implementation that the model is readily implemented with the object-oriented method on the Java platform. Since a large volume
of computation is required for determination of the time history for real life buildings with large numbers of components, the computer implementation is essential for any practical application of the model.

Important input parameters of the model are the life spans and devaluation rates of the different classes of building components. Values of devaluation rates which have been determined by extensive studies in other countries [2] remain to be verified in Russia. The life span depends strongly on the quality of the components and their environment in the building, so that different values must be specified for average, poor or good conditions. Other important input parameters are the renovation cost ratio and the significance values of the various classified sets. Physical, chemical and statistical research is required to obtain reliable and sufficiently accurate numerical values for these input parameters under varying conditions in engineering practice.

The possibility to relate the accumulated renovation costs of buildings to their initial value, and thus to the investment costs for the building, permits the use of the model as a decision support tool. The devaluation diagrams for alternate designs of the buildings using components of different quality and life span are readily studied. The influence on the accumulated renovation costs of different groupings of the building components in renovation groups can also be studied with the model. Research on these aspects of the novel approach is under way and will be published in a companion paper at a later point in time.

In summary, it can be concluded that the research on which this paper is based has opened the way for a broad spectrum of research and development and for beneficial applications in engineering practice.
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ИНТЕГРИРОВАННАЯ МОДЕЛЬ ОПРЕДЕЛЕНИЯ ФИЗИЧЕСКОГО ИЗНОСА ЗДАНИЯ И ПЛАНИРОВАНИЯ РЕМОНТНЫХ РАБОТ

Рассмотрен подход к моделированию физического износа жилых зданий с целью оптимизации ресурсов при планировании и проведении ремонтных работ. В соответствии с предложенным методом, на первом этапе строятся модели физического износа отдельных элементов здания, используются нормированные значения эксплуатационного ресурса и нормированные значения срока службы, а также вводятся дополнительные переменные. На втором этапе происходит синтез моделей физического износа здания из ранее построенных моделей отдельных элементов. На третьем этапе вводятся параметры, позволяющие моделировать процесс планирования ремонтных работ для отдельных элементов — значения эксплуатационного ресурса элемента до и после проведения ремонта, а также стоимость ремонтных работ. На заключительном этапе модели, разработанные на предыдущем этапе, соединяют в единую модель, с помощью которой становиться возможным изучение различных сценариев проведении ремонтных работ в данном здании.

Ключевые слова: жилые здания, физический износ, ремонтные работы, планирование, автоматизация.

Библиографический список


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