

Article

Influence of Age on the Technical Wear of Tenement Houses

Jarosław Konior , Marek Sawicki and Mariusz Szóstak * 

Department of Building Engineering, Faculty of Civil Engineering, Wrocław University of Science and Technology, 50-370 Wrocław, Poland; Jaroslaw.konior@pwr.edu.pl (J.K.); marek.sawicki@pwr.edu.pl (M.S.)

* Correspondence: mariusz.szostak@pwr.edu.pl; Tel.: +48-71-320-23-69

Abstract: The research presented in the article, which includes methods, models, and conclusions, contains synthetic and analytical model solutions concerning the problems of the technical maintenance and wear of residential buildings with a traditional construction. The cause and effect relationships between the occurrence of damage in the elements of tenement houses (treated as proof of their maintenance conditions), and the size of the technical wear of these elements were determined using a representative and purposefully selected sample of 102 residential buildings erected during the second half of the nineteenth and early twentieth centuries in Wrocław's "Downtown" district. Quantitative damage analysis, which was carried out using empirical (visual) methods of assessing the technical condition of a building, indicates the type and size of damage to the building's elements that are characteristic for the relevant maintenance conditions. Research concerning the cause–effect relationships ("damage–technical wear") in observed states allows for a numerical approach to the impact of building maintenance conditions on the degree of the technical wear of its components. The maintenance and exploitation conditions determine the degree of the technical wear of the elements of an old residential building. The exploitation condition of these buildings is manifested by damage to elements caused by water and moisture penetration, which is especially important for poorly maintained buildings. The article shows that the age of the elements of an old residential building with a traditional construction is of secondary importance in the process of the intensity of losing its serviceability value. It was calculated that no more than 30% of the damage of building components is explained by the passage of time, and it is therefore not age that determines the course of the technical wear of the elements of the analyzed tenement houses.

Keywords: tenement houses; technical wear; defects; age; maintenance; durability



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1. Introduction

The present situation of housing—one of the basic human needs—is understood as a social and economic stimulus for the development of each family. It is determined by the influence of cultural, political, and technical factors of the period, which largely corresponds to the average life expectancy of one generation [1].

The intensive development of housing in the 20th century resulted almost exclusively from conducted investment works. At that time, the value of renovation works in Poland was at the level of 1–2% in relation to newly erected building objects [2], while in Western European countries, the share of renovation works in the total construction production was equal to 40–50% [3,4]. As a result of such activities, housing stock was significantly reduced. Although the cultural, social, and economic need to renew old housing began to be noticed in the nineties, the negligence that goes back many years was not fully compensated for until today [5].

A breakthrough in the approach to this issue at the end of the 20th century can be seen to be the responsible and comprehensively thought-out method of reconstructing municipal housing estates [6]. This mainly applies to downtown urban routes, which is due to the fact that cultural and social decisions about their reconstruction are starting to exceed technical aspects [7]. An additional factor supporting the profitability of undertaking renovation and

modernization works of downtown tenement houses are economic considerations, which are gaining new significance with the rapid increase in land and real estate prices [8].

Currently, there is an urgent need to develop principles for the comprehensive technical assessment of residential buildings erected using traditional methods. This is the stage that determines the appropriate method (well recognized in, e.g., [9–17]) of their technical and social reconstruction. This article is meant to be a contribution towards determining the impact of factors related to the broadly understood sphere of the maintenance of downtown tenement houses on their technical wear.

A correct assessment of the technical condition of residential buildings (systematically and reliably conducted) is the basis for the widely understood organization of their technical service [18], and in particular for the organization of repairs of a fixed type, size, and scope, e.g., according to [19]. This assessment, supported by the diagnosis of the impact of housing maintenance conditions, is also the basic source of information in the rational management of housing resources, e.g., according to [20,21].

In the process of multi-criteria analysis of the technical condition of buildings, the study of the technical wear of buildings and structures is of fundamental importance, e.g., [22–24]. Regardless of the methods used to evaluate an object, the degree of technical wear of its elements is the basic parameter when making decisions about the future of a residential building [25]. It should also be remembered that the examination of the technical condition of building elements must be multifaceted. The final determination of the value of the technical wear degree should reflect theoretical conditions and material facts, social, and economic premises, and individual knowledge and experience of the evaluator [26].

There is no doubt that each type of housing estate is different and not always comparable within typological research groups. Therefore, there are different ways to technically maintain different groups of objects, and the types of damage that are specific for each group must then also be different [27]. A detailed analysis of this damage, which is proof of the maintenance conditions of residential buildings, provides information on the broadly understood exploitation processes of the buildings in the past and also forecasts the length of their remaining service life in the future. The issue gains additional significance when the investigation of the technical condition indicates a slight variation in the degree of the technical wear of building elements. This variation can be explained by the influence of time, which is the only independent variable. The advantage of many random dependent variables is so great that it leads to the undertaking of research on the unexplained part of technical wear with regards to the magnitude of the impact of maintenance conditions on the accelerated destruction of residential buildings.

The problem of the analysis of the technical process of the wear of building objects over time is presented quite widely in technical literature [11,12,15,28–31]—but unfortunately it is more descriptive (theoretical) than normative (with regards to applications). In order to determine the degree of technical wear, as a parameter describing the process, various types of information about an object are necessary, e.g., durability, dependence between the technical age and the maintenance conditions or utility purpose, and also the share of individual elements in the cost structure.

Such data, often fragmentary, are published from time to time in various sources (e.g., [9,15,17,31–33]), and therefore their full presentation, systematization, and example of use seems justified. Moreover, it should be remembered that the examination of the technical condition of building elements must be multifaceted. The final determination of the value of the technical wear degree should reflect theoretical conditions and material facts, and also economic and social reasons and the individual knowledge and experience of the evaluator. The purpose of the research concerning the process of the technical wear of buildings should answer the fundamental question: what degree of technical wear is caused by the age of the element (inevitable), and what is the result of accelerated deterioration (until slowdown)?

In the process of multi-criteria analysis of the technical condition of buildings, the investigation of the technical wear of buildings and structures is very important. Regardless

of the methods used for assessing an object, the degree of technical wear of its elements is the basic parameter when making decisions about the future of a building, especially a residential building. The problem of the analysis of the process of the technical wear of buildings is presented quite widely in technical literature [11,12,14,28,34–39].

There are various criteria for assessing the degree of wear of an object, which are published in reference literature. English and German literature [11,14,23,32,40–42] is consistent regarding this matter, and adopts a three-level division at a general level (0–30%, 31–70%, and 71–100%). In the case of specific location data and the identified maintenance and service conditions of a facility, it adopts a five-stage classification with slightly flexible thresholds regarding the class of the wear. Using the recommendations specified in this way, a five-level division prepared on the basis of Sroczyk's investigations, and disseminated by Winniczek [43], was adopted in this study. This allows a more precise classification of an element to a specific group of wear to be adopted. The technical condition of a facility is therefore determined as good with wear at a level of 0–15%, satisfactory with wear at a level of 16–30%, average with wear at a level of 31–50%, poor with wear at a level of 51–70%, and bad with wear at a level of 71–100%. It should be mentioned that an object in a bad technical condition should be subjected to demolition or comprehensive renovation, but only if these activities are both socially and economically justified.

In subject literature [12,15,43–52], several methods of determining the technical wear degree of buildings were described. In fact, the authors of studies [12,15,43,44,50,51] present the same approach to this issue, except that, due to the non-standardized nomenclature, they use different nomenclature and classifications. The main ideas of determining the size of wear are consistent with the practices in this field, which were used by assessors in the pre-war period [53–55] and which are still used in Western countries. Despite discrepancies in mathematical formulas, these formulas are based on the assumption that technical wear is a function of time, t , in the assumed durability of a building object T . In turn, the influence of external factors, which have a destructive effect on an object, can be assessed on the basis of detailed technical investigations in specific locations.

2. Research Method

2.1. Technical Characteristics of a Group of 102 Residential Buildings

The subject of the descriptive characteristics [56] concerns tenement houses in a separate part of the Downtown district of Wrocław, Poland. The buildings are situated along downtown streets of secondary importance in an urban layout that has remained unchanged for years. They are front buildings, and also outbuildings with a modest architectural design and economical functional standard. Most of the 102 tenement houses were erected in the second half of the nineteenth century, until the outbreak of World War I. The oldest, dating back to the year 1818, analyzed tenement house is presented in the Figure 1.



Figure 1. The example of the analyzed tenement house.

The detailed technical characteristics of the group of downtown tenement houses, which are homogeneous in terms of functionality and their material and structure, refer to the elements described in the following building subsystems:

1. Load-bearing structure:
 - brick foundations—with a low load-bearing capacity and a complete lack of horizontal and vertical anti-moisture insulation;
 - brick construction walls—made of solid ceramic brick with a class of 7.5–10 MPa and cement-lime mortar or lime mortar with a class of 0–0.4 MPa;
 - massive basement ceilings—mostly brick section vaults on steel beams;
 - inter-story ceilings—mostly on wooden beams with a slide-in joint, and plastered ceiling linings; in a few cases they were changed into WPS (beam-and-block floor) or Klein ceilings, or the wooden beams were reinforced with steel beams;
 - stairs—with a steel structure of stair flights, wooden treads and risers, and wooden or brick landings, often with a decorative railing; brick stairs to the basements;
 - roof trusses—wooden (rafter-purlin truss, queen post truss, purlin-post, purlin-collar beam, purlin-stool, collar beam-stool).
2. Finishing elements:
 - doors—panelled or solid plate doors to flats; interior doors-panelled, solid plate, with or without glazing; decorative entrance gate to the building;
 - windows—double or single casement windows in flats; semi-casement or single frame casement windows in staircases;
 - internal plasters—smooth lime;
 - external plasters (facades) —smooth or mottled, richly decorated;
 - roof coverings—asphalt roll roofing on full boarding on the flat part of roofs; tiles or slates on the steep part of roofs;
 - flashings—gutters and downspouts made of galvanized metal sheet.
3. Installations:
 - water and sewage—enclosed or partially enclosed;
 - electric—surface or flush mounted;
 - gas—not covered, delivered to flats.

2.2. Selection of the Research Sample

The research sample, covering 102 technically assessed residential buildings from Wrocław's Downtown district, was selected from a group of 160 examined buildings. The overriding criterion for the selection of the sample was the obtaining of a comparable group of objects. Mutual comparability of downtown tenement houses meant:

- age coherence, i.e., a similar period of erection, maintenance and exploitation with regards to historical and social aspects;
- compact development in the urban layout that has remained unchanged for years;
- similar location along downtown street routes with an urban, but not representative, character;
- construction and material homogeneity, especially regarding the load-bearing structure of buildings;
- identical functional solutions, which are understood as the standard of apartment amenities and furnishings in force at that time, and also a specific standard of living of residents.

A method of selecting the research sample at the level of greater detail was based on the mutual similarity of all technical solutions of downtown tenement houses.

The selected research sample, according to the criteria presented above, is representative with regards to one of the concepts (specific for the adopted purpose of the study) of representativeness [57]. Thus, the typological representativeness of the sample into which the desired types of homogeneous variables are classified can be considered. Due

to the fact that the structure of the population and its properties were well recognized earlier, such a selection of the research sample can also be considered to be deliberate. It should be noted that the sample may not be representative in terms of the distributions of the examined variables, which may—for the adopted significance level—not correspond to the analogous distributions in the general population. It is also not known—at this stage of the research—whether the selected sample is representative due to the correspondence between its variables and the identically defined variables in the entire set of downtown residential buildings.

2.3. Normal Wear

The theoretical methods of determining the normal technical wear of the analyzed tenement houses and their elements involved the linking of it with time parameters, i.e., the current service life of the building t and its expected total service life T .

The obtained results of the measurements of the degree of technical wear of the tenement houses and their elements are summarized in Table 1.

The technical wear of horizontal and vertical damp-proof insulations, which reaches almost 100%, can be considered to be insignificant in the size of the wear of the entire building. This is due to their small, equal to 1% share, in the total cost of the building. From the group of 23 technically examined elements, the 10 elements with the highest share in the building (65% in total) were selected for further analysis—Figure 2.

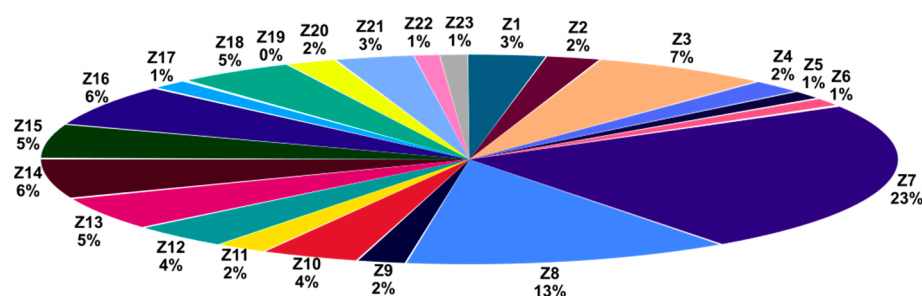


Figure 2. Average share of building elements in tenement houses.

The technical wear degree of these elements has been calculated theoretical way as a function $Zt = f(T)$ [39,46–51] and as a result of building's technical inspections executed by engineering experts.

The facades (Z20) are worn to the highest degree (56.77%), and the massive ceilings above the basements (Z4)—to the lowest degree (43.16%). The dispersion of the results is confirmed by the high values of the standard deviation and the coefficient of variation. They are the largest for the Z20 facades (24.66% and 43%, respectively), and the smallest for the Z2 foundations (8.83% and 20%, respectively). Other statistical quantities, such as the average of the numbers that deviate from the mean, variance, and median, also reach maximum and minimum values in the evaluation of the same elements. Although in the case of the facade the presented results are confirmed by the description of their destruction, damage, and various maintenance conditions, the results concerning the foundations—due to the difficulty of macroscopic assessment—should not be considered to be reliable. The amount of technical wear of the building, as a whole, was calculated whilst taking into account the share of individual elements in the building's total cost. It is worth noting that the two basic structural elements (the overground construction walls Z7 and the inter-story ceilings Z8) account for over one-third of the cost of the total financial outlay for the reconstruction of the facility. For a building with an average degree of technical wear equal to 48% and a different proportion of Z1–Z23 elements, the values of the standard deviation and the variation index are equal to 10.94% and 23%, respectively.

Technical wear of an apartment house as a whole has been calculated the following way:

$$Z = ZS2 + ZS3 + ZS4 + ZS7 + ZS8 + ZS9 + ZS10 + ZS13 + ZS15 + ZS20 \quad (1)$$

if:

$$ZS_i = S_i \times Z_i \quad (2)$$

where as

S_i —element's share in the building (%)

ZS_i —technical wear of the element as a part of the building's technical wear (%)

Z_i —element's technical wear (as a result of inspections) (%)

The obtained and calculated data for determining the technical wear of an exemplary tenement house is presented in the Table 2.

The results of measurements obtained by a team of experts consisted of

- 1 architect;
- 1 structural engineer;
- 1 mechanical/sanitary engineer;
- 1 electrical engineer;
- 2 quantity surveyors;
- 1 technician/administrator.

The average workload needed for the technical assessment of each tenement houses has been calculated as follows:

- desk top study of multidiscipline design and archive documents—2 days for 5 people;
- technical investigations and surveys—3 days for 7 people;
- generating calculations and reports—2 days for 5 people.

The experts were updated with additional information, and the scope of which was presented in the previous section of the paper, allowed for the presentation of indirect conclusions. They mainly concern the technical condition of the maintenance of elements of downtown tenement houses—the frequency of their damage and destruction, and the scope of their repairs, replacement, and reinforcement. Some of them, formulated on the sample of 102 buildings, are as follows:

- the dampness of underground walls is observed in 42 tenement houses, and the dampness of walls above ground in 36 of them. Five buildings, in the years 1983-1987, were dried using electroosmosis and protected using electroinjection. In two cases, the treatments turned out to be ineffective;
- scratches or cracks in structural walls are noticed in 10 buildings;
- corrosion of steel beams in the ceilings above the basements is found in 59 buildings, and in 28 cases it is surface corrosion;
- biological infestation of wooden ceilings between floors occurs in 32 buildings, and it mainly concerns the most endangered parts of the ceilings. However, extensive and advanced damage is only observed in 13 buildings;
- biological infestation of the roof truss elements concerns 59 buildings, six of which have a very poor general condition of the truss. In addition, 16 buildings have visible dampness of the roof structure due to leaky roofing.

Table 1. Measurement results of the degree of technical wear of the tenement houses and their elements.

Class of Technical Wear	State of the Maintenance of Building Elements	Observed Technical Wear of Building Elements (%)	Foundations Z2	Walls of Basement Z3	Solid Floor over Basement Z4	Main Walls Z7	Inter-Storey Wooden Floors Z8	Stairs Z9	Roof (Rafter Framing) Z10	Window Joinery Z13	Inner Plasters Z15	Facades Z20	Apartment House as a Whole Z
1	2	3	4	5	6	7	8	9	10	11	12	13	14
I	very well cared	0–15	0	0	1	0	0	0	1	2	2	5	0
II	above than average	16–30	7	12	23	16	3	17	12	17	10	17	2
III	average	31–50	83	57	45	61	54	49	42	52	59	22	60
IV	poor	51–70	11	24	23	25	37	32	43	27	22	27	37
V	very poor	71–100	1	2	3	0	8	4	4	4	9	28	3
Total number of analyzed apartment houses			102	95	95	102	102	102	102	102	102	99	102

Table 2. Technical wear of an apartment house as a whole.

	Foundations Z2	Walls of Basement Z3	Solid Floor over Basement Z4	Main Walls Z7	Inter-Storey Wooden Floors Z8	Stairs Z9	Roof (Rafter Framing) Z10	Window Joinery Z13	Inner Plasters Z15	Facades Z20	Apartment House as a Whole Z
S_i	4.46	2.47	0.47	33.99	8.59	0.50	2.06	5.79	4.74	4.23	
ZS_i	2.68	1.73	0.28	23.79	6.87	0.28	1.13	4.05	3.32	3.38	68.95
Z_i	60	70	60	70	80	55	55	70	70	80	

When considering this issue with regards to the decision on the advisability of renovation and modernization of buildings, the entire condition of structural elements was analyzed. Five basic elements were distinguished, i.e., underground structural walls Z3, main walls above ground Z7, massive ceilings above the basements Z4, inter-story wooden ceilings Z8, and also roof structures Z10. In the group of 102 assessed objects, there are nine buildings in which a significant destruction of all the distinguished elements was observed, and six buildings in which the destruction concerned four out of five analyzed elements. Therefore, it can be briefly concluded that the renovation of 15 objects in the group of 102 could be ineffective.

2.4. Accelerated Wear

Proof of the accelerated technical wear of building structures is damage to their components. A detailed description of damage to selected elements of downtown tenement houses takes into account their four-group classification at the level of general synthesis—Table 3. It must be remembered however that generically integrated elementary damage is separated therefore their total number is 30—Table 3. There is also a very important assumption made, according to which pinpointed damage is described using number 1 (appears), and its lack using 0 (does not appear). This is due to the fact that the group of experts only identified damage in the analyzed buildings that is independent of their natural wear, i.e., that which occurs to a great extent. They were describing it with clear and decisive qualitative features [56]: “significant”, “very strong”, “strong”, “total”, and similar ones.

Where particular groups refer to

- I mechanical defects of the structure and surface of elements
- II defects of elements caused by water penetration and humidity migration
- III defects symptomatic of the loss of the original shape of wooden elements
- IV defects of wooden elements attacked by insects—technical pests of wood

The reasons for the accelerated wear of the residential buildings may be of a technical, organizational, social, or other nature. They can occur at various stages of the “building’s life”, i.e., at the design, implementation, and exploitation (use) stages. The causes related to the broadly understood external and internal impact of the surroundings on a building were identified as those that have a direct impact—the accelerated destruction of downtown tenement houses. A division of the factors of the intensified process of technical wear of a residential building is proposed. In this division, a building is treated as a source for satisfying housing needs, and it is subjected to multiple impacts. By adopting such a perception of an object, the following causes of damage to the building’s elements (independent of their natural wear) were distinguished: A—external factors, which are independent of the conditions of maintenance and use of the building; B—external and internal (“hereditary”) factors, when there is no or only a theoretical (cost) possibility of reconstructing the satisfactory technical condition of the building; and C—internal factors, when the reconstruction of the building’s condition is solely a result of improving the conditions of maintaining and using the building. This division, in a detailed elaboration, is as follows:

- A. external factors, which are independent of the methods of maintaining and operating the building:
 - pollution of the district’s atmosphere with carbon, sulfur, and lead oxides (chemical corrosion of bricks and mortar, as well as metal flashings);
 - multiple sudden changes in the level of the groundwater table in the 19th and 20th centuries (flood waves, flooding of basements);
 - additional external dynamic loads (e.g., from the passage of trams, from vibrating elements of a heat and power plant);
- B. external and internal (initial) factors related to the lack of protection of a building against progressive destruction and changes in the function of the facility:

- a lack of horizontal and vertical damp-proof insulations;
 - a lack of remote delivery heating installations;
 - a lack of gravity ventilation of rooms;
 - difficulty of ventilating apartments in the longitudinal construction layouts;
 - low thermal insulation of walls;
 - change in the function of parts of a building from commercial to residential, or vice versa;
 - warfare (especially in 1945);
 - change in the type of building layout, e.g., from compact to semi-compact as a result of war damage and later demolitions (internal structural walls begin to function as unplastered gable walls);
- C. internal factors related to the improper maintenance and use of buildings:
- improper exploitation, failure to rectify faults, and a lack of maintenance of a building;
 - failure to carry out current repairs, demolding and impregnation works, as well as preventive and major repairs of a building;
 - inappropriate technology of drying the building's walls (plaster cracking);
 - covering facade plasters with low-quality paint coats that have aggressive properties and an inappropriate chemical composition;
 - frequent sewage system failures (flooding of basements with faces);

Modifications that were carried out by tenants, which involved a complete change of the functions of rooms (e.g., locating bathrooms in a part of the kitchen and directly on wooden ceilings, or moving a worn-out surface installation under plaster).

2.5. Research Model

The theoretical model of the technical wear of the elements of residential buildings is a function of time t and their assumed durability T . The comparative analysis of the observed and theoretical wear shows that it is practically impossible to determine the exact form of the dependence between the wear of an element and its age. This difficulty results from the influence of many factors, which are different for each residential building, and which can only be described by a complicated mathematical model. In this situation, when there is a need to determine the trend of this phenomenon, low complexity models should be selected while taking into account that compliance with empirical observations should be considered as the selection criterion. Therefore, the research was limited to the searching for trend functions among linear, power (multiplicative), exponential, and hyperbolic relationships [58–64].

Table 3. Classification of damage to selected elements of tenement houses.

		Floor		Main Walls		Roof			Supply Systems			Joinery		Plaster		
		over Basement	Inter- Story	of Basement	of Over- ground	Stairs	Construction	Roofing	Flashing	Water- Sewerage	Wiring	Gas	Window	Door	Inner	Outer
gr. no.	Type of Defect	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
I	Mechanical defects					#				#	#	#	#	#	#	#
	Leaks							#		#		#	#	#		
	Cracks of steel elements								#	#		#				
	Mechanical decrements of bricks, mortar, roofing, flashing	#		#	#	#		#	#							
	Decrements caused by rotten bricks, mortar	#		#	#										#	#
	Paint coatings peeling off													#	#	#
	Paint coatings falling off														#	#
	Cracks of bricks, plaster	#		#	#										#	#
	Scratching of walls, plaster		#		#										#	#
	Loosening of plaster														#	#
II	Plasters falling off														#	#
	Signs of permanent damp	#	#	#	#		#	#					#		#	#
	Weeping	#	#	#	#	#	#	#					#		#	#
	Biological corrosion of bricks and corrosion of steel elements			#	#				#	#		#				
	House fungus		#					#							#	#
	Mold and decay			#	#								#		#	#
	Localized corrosion of steel beams	#				#										
	Surface corrosion of steel beams	#				#										
	Pitting corrosion of steel beams	#				#										
	Flooding of foundations	#														
III	Wooden beams of floor affected by the dynamic activity of human weight		#													
	Deformation of wooden beams		#													
	Skewing of joinery												#	#		
	Warping of joinery												#	#		
	Stratification of wooden elements						#									
IV	Partial deterioration of wooden elements attacked by pests					#	#						#	#		
	Total deterioration of wooden elements attacked by pests		#				#						#	#		

2.5.1. Nonlinear Regression

The parameter values of the studied models were selected using the non-linear regression method [58–60,63,64]. Therefore, a random (dependent) variable that represents the degree of the technical wear of a building element was designated as Z (with the values $z_1, z_2, \dots, z_n$), and the age of the element as t (with the values $t_1, t_2, \dots, t_n$). Then, according to the rules of nonlinear regression, the null hypothesis H_0 was adopted. According to this hypothesis, the created model does not explain the systematic variability of variable Z with regards to t (independent variable), which was described by the regression coefficient γ and increased by the constant random component ξ :

$$Z = \xi + f(t, \gamma) = \xi + \gamma t \quad (3)$$

An important role in Equation (1) is played by the random component ξ , which was included in the tested model for four general reasons:

- the studied dependence is random;
- it was not possible to include in the model all the factors that influence the development of the dependent variable;
- after the comparative analysis, there were doubts if the assumed analytical form of function $f(t)$ fully corresponded to the real form of the tested compound;
- the macroscopic technical assessment data, on which further modelling was based, was affected by measurement errors.

The biggest obstacle for the correct creation of the model when using the nonlinear regression method was the failure to specify the size of parts $\xi_1, \xi_2, \dots, \xi_k$, which are the elementary components of the random constant ξ , and which should include the factors of the two-type influence:

- to a great extent—when referring to the maintenance conditions of downtown residential buildings and the subjectivity of their technical assessment by each of the adjudicating experts;
- to a small extent—when referring to the type of measuring equipment and measurement errors, the used technical assessment method and its accuracy, the incomplete knowledge about the technical condition, and the age of the tested element.

The only solution when carrying out further analysis of the existing situation was to divide the entire model (written by Equation (1)) into a part that is explained by the sought model (which depends on regression), and a part that is unexplained by this model, but is defined as the residual component ξ , which includes all the above-mentioned factors being taken into account during the technical assessment of downtown tenement houses.

The search for the numerical values of parameters γ and ξ was carried out using the least squares method [60,64], with the use of which estimators corresponding to constant A ($=\xi$) and the regression coefficient B ($=\gamma$) were determined. Afterwards, for the slope γ of the regression function, the value of the Student's T-statistic and the number of degrees of freedom were determined, which for the k -element is $k = 1$, and for the residuals is $n-k$. For the Student's T-distribution with $n-k$ degrees of freedom, the observed significance (probability) level was determined as an indicator of the null hypothesis H_0 in the Fisher test. This test was selected in order to verify the significance level. If the observed significance level $p(A, B)$ was lower than the assumed significance level $\alpha = 0.05$, then this fact proved that the null hypothesis, which assumed no influence of the independent variable t ($=X$) on the dependent variable Z ($=Y$), was unreliable. As a result, an alternative hypothesis with the opposite meaning was adopted, but only in relation to the specific regression function that was described by the determined estimators.

It was assumed that the initial model of a physical phenomenon, the independent variable of which is time, should be as simple as possible. Therefore, in addition to the commonly used parabolic relationships, four types of mathematical functions were sought using the nonlinear regression method:

- linear model: $Y = A + BX$;
- power model: $Y = AX^B$;
- exponential model: $Y = \exp(A + BX)$;
- hyperbolic model: $1/Y = A + BX$.

Table 4 presents the results of the modelling of the 10 tested tenement house's elements using nonlinear regression.

2.5.2. Analysis of Variance

The analysis of variance explains the variability of the assumed function according to one of the models that were proposed above, while at the same time keeping the division into the part explained by the model and the part explained by the residual component [60,62–64]. By matching the proposed relationship with the observed (empirical) data, the total sum of the squared deviations of the variable that is dependent on the mean was divided into the sum of squared deviations, which is explained by the linear regression with regards to the independent variable, and the sum of squares not explained by this regression. The mean square of the deviations that are not explained by regression is the variance $[d(\xi)]^2$ of the residues. The positive root of this quantity is the standard deviation $d(\xi)$ of the residuals.

The value of the standard deviation of residuals provided information about the average value of the deviations of the observed values of the variable Z_e that is dependent on the theoretical values Z_t . Therefore, it indicated the degree to which the model was adjusted to empirical data. However, the coefficient of determination R^2 , calculated as the quotient of the sum of squared deviations (which was explained by regression) and the total sum of squared deviations, was adopted as the correct measure of the adjustment. The value of the coefficient of determination R^2 , given as a percentage, provides information about the size of the element's wear differentiation that was observed in the test and which was explained by its regression in relation to the age of the building.

2.5.3. Residual Analysis

When estimating the trend model, apart from finding the estimates of the structural parameters, some basic parameters of the stochastic structure are also estimated [58,62–64]. In turn, knowledge of the assessments of these parameters allows certain measures of the degree of compliance of empirical data with the data resulting from the trend function to be calculated. This provides the basis for the assessment of the degree of accuracy to which the conclusions based on the estimated trend function can be drawn in the future.

The basic parameter of the stochastic structure of the trend model that was most correctly selected in the paper was the variance of the random component $[d(\xi)]^2$. Due to the fact that the variance of the random component in the general population was not known, it was estimated on the basis of a sample group with $n-k$ ($k = 1$) degrees of freedom for the parabolic model. Therefore, it was assumed that the unbiased estimator of the random component is the variance of the residual component, which is expressed by the following formula:

$$[d(\xi)]^2 = \frac{\sum_{i=1}^n (Ze_i - \bar{Z}_t)^2}{n - 1} \quad (4)$$

The residual component variance is a measure of the order of magnitude of the deviations between the random variables Ze_i and the trend function.

Table 4. The results of modelling when using non-linear regression, and the analysis of variance and residuals.

Seeking of Alternative Functions $Z_t = f(t)$ Using the Non-Linear Regression Method										
Elements	Mathematical Formulas	Non-Linear Regression				Variance Analysis				
		Estimators		Probability Level		Model		Residuum		Determination Coef.
		Constant A	Regression c. B	P(A)	P(B)	Df	Square Sum	Df	Variance	R ² (%)
Foundations Z2	Linear model	38.3112	0.0767	0.0000	0.1075	1	204.185	100	77.419	2.57
	Power model	2.7722	0.2277	0.0000	0.0427	1	0.154	100	0.036	2.04
	Exponential model	3.6223	0.0019	0.0000	0.0687	1	0.125	100	0.037	3.28
	Hyperbolic model	0.0272	−0.0001	0.0000	0.0502	1	0.000	100	0.000	3.78
Walls of basements Z3	Linear model	40.9788	0.0618	0.0000	0.3403	1	130.635	93	142.183	0.98
	Power model	2.9162	0.1992	0.0000	0.1808	1	0.115	93	0.63	0.92
	Exponential model	3.6682	0.0016	0.0000	0.2556	1	0.083	93	0.064	1.39
	Hyperbolic model	0.0264	0.0000	0.0000	0.2043	1	0.000	93	0.000	1.73
Solid floors over basements Z4	Linear model	47.1248	0.0442	0.0000	0.5886	1	66.797	93	226.729	0.32
	Power model	3.7306	0.0062	0.0002	0.9769	1	0.000	93	0.134	0.00
	Exponential model	3.7470	0.0005	0.0000	0.8035	1	0.008	93	0.134	0.07
	Hyperbolic model	0.0272	0.0000	0.0000	0.8982	1	0.000	93	0.000	0.02
Main walls Z7	Linear model	33.4729	0.1372	0.0000	0.0274	1	652.889	100	130.344	4.77
	Power model	2.4681	0.2956	0.0002	0.0427	1	0.259	100	0.061	3.05
	Exponential model	3.5488	0.0027	0.0000	0.0440	1	0.256	100	0.061	3.99
	Hyperbolic model	0.0283	−0.0001	0.0000	0.0696	1	0.000	100	0.000	3.25
Inter-storey wooden floors Z8	Linear model	51.9130	0.0229	0.0000	0.7856	1	18.236	100	244.987	0.07
	Power model	3.3811	0.1268	0.0000	0.4386	1	0.048	100	0.079	0.60
	Exponential model	3.8508	0.0011	0.0000	0.4689	1	0.042	100	0.079	0.53
	Hyperbolic model	0.0230	0.0000	0.0000	0.2656	1	0.000	100	0.000	1.24
Stairs Z9	Linear model	34.4926	0.1509	0.0000	0.0126	1	1269.919	100	196.666	6.07
	Power model	3.1387	0.1552	0.0000	0.0004	1	1.206	100	0.090	4.78
	Exponential model	3.4810	0.0038	0.0000	0.0038	1	0.083	100	0.094	8.06
	Hyperbolic model	0.0323	−0.0001	0.0000	0.0021	1	0.001	100	0.000	9.04
Roof (rafter framing) Z10	Linear model	33.6762	0.2190	0.0000	0.0000	1	4636.470	100	169.804	21.45
	Power model	3.0760	0.1907	0.0000	0.0001	1	1.692	100	0.096	15.00
	Exponential model	3.4876	0.0050	0.0000	0.0000	1	2.416	100	0.089	21.41
	Hyperbolic model	0.0326	−0.0001	0.0000	0.0000	1	0.002	100	0.000	16.13
Window joinery Z13	Linear model	21.3298	0.3535	0.0000	0.0000	1	7525.724	100	188.233	28.56
	Power model	1.1864	0.6157	0.0007	0.0000	1	5.464	100	0.092	17.27
	Exponential model	3.1651	0.0085	0.0000	0.0000	1	4.396	100	0.103	29.99
	Hyperbolic model	0.0426	−0.0002	0.0000	0.0000	1	0.004	100	0.000	26.07
Inner plasters Z15	Linear model	42.0942	0.0798	0.0000	0.3476	1	242.623	100	272.446	0.88
	Power model	1.8372	0.4468	0.0233	0.0138	1	0.832	100	0.132	0.92
	Exponential model	3.6030	0.0026	0.0000	0.1756	1	0.257	100	0.138	1.83
	Hyperbolic model	0.0333	−0.0001	0.0000	0.0915	1	0.000	100	0.000	2.82
Facades Z20	Linear model	28.6270	0.3512	0.0001	0.0000	1	10,771.473	97	509.734	17.89
	Power model	2.1473	0.4168	0.0000	0.0000	1	9.868	97	0.236	15.15
	Exponential model	3.1666	0.0092	0.0000	0.0000	1	7.441	97	0.261	22.74
	Hyperbolic model	0.0523	−0.0003	0.0000	0.0000	1	0.010	97	0.000	25.30

An additional parameter, which supplements the variance of the residual component, was the mean of deviations of residuals $c(\xi)$ between the measured degree of the technical wear of the elements of the analyzed buildings and the one that was obtained from the model:

$$c(\xi) = \frac{\sum_{i=1}^n (Ze_i - \bar{Z}_t)}{n} \quad (5)$$

Such a constructed pair of measures of the correctness of selecting the trend function is of significant importance when analyzing the durability of building elements. By assuming the estimated service life of a residential building as independent variable T , the course of the dependence between the variance of residuals and their mean deviations as a function of durability was investigated: $[d(\xi)]^2 = f(T)$ and $c(\xi) = f(T)$. In a properly constructed model, variance $[d(\xi)]^2$ should reach the minimum for literature values (e.g., [58,63]) of durability ($T = 120$ years), and the mean of deviations should be close to zero $c(\xi)$.

The variability of these functions for the inter-storey stairs of tenement houses is shown in Figure 3.

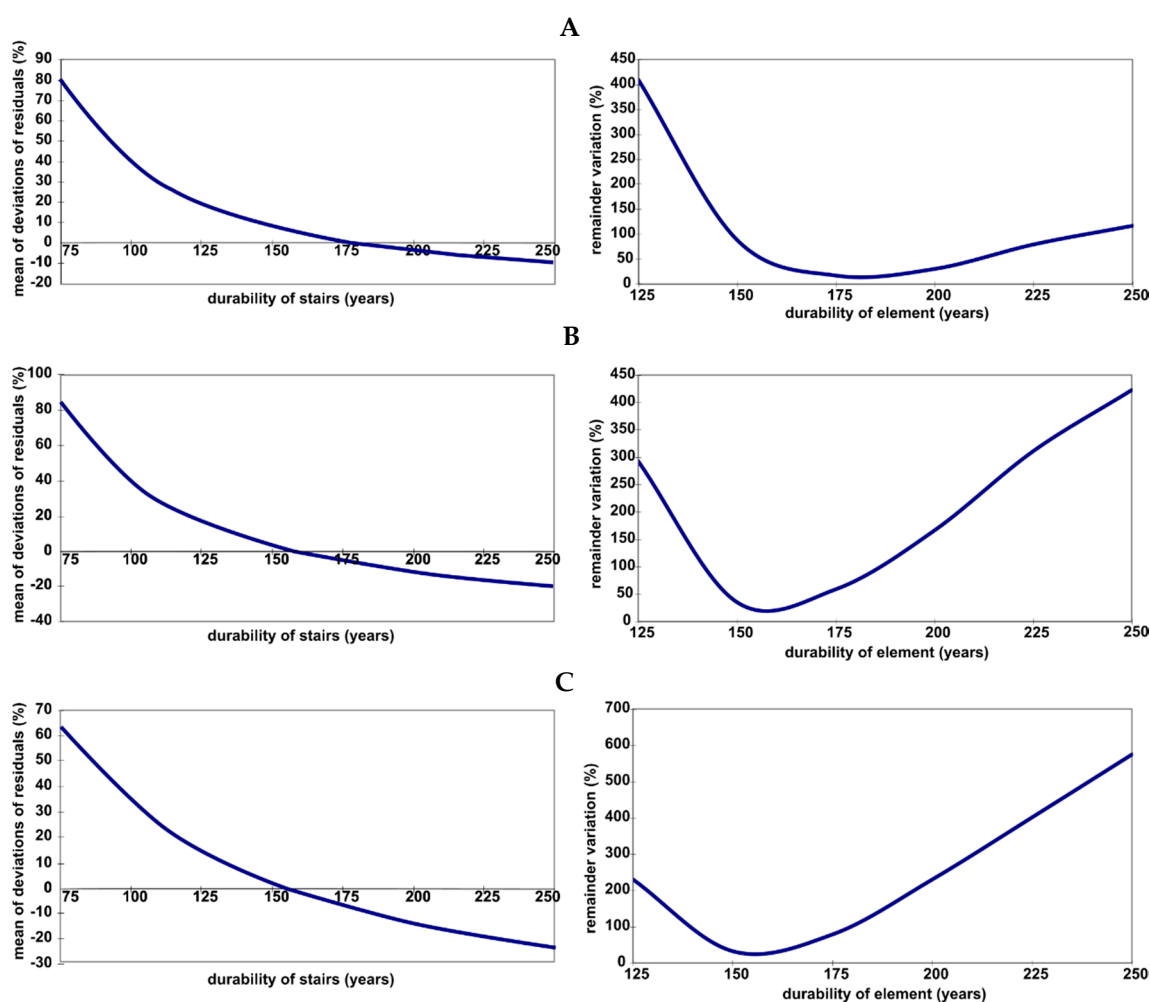


Figure 3. Variance of residuals and mean deviations as a function of durability of inter-storey stairs of tenement houses with: (A)—better than good maintenance of a tenement house; (B)—good maintenance of a tenement house; (C)—poor maintenance of a tenement house.

Both $[d(\xi)]^2$ and $c(\xi)$ are to control the correctness of the trend function selection is crucially important for the analysis of the expected life of building elements. Assuming the expected time of an apartment house exploitation to be an independent variable T , a course of relationship of the remainder addends and their deviations average was tested

as a function of the expected life: $[d(\xi)]^2 = f(T)$ and $c(\xi) = f(T)$. In a correctly constructed model, the variance $[d(\xi)]^2$ should reach the minimum for values of the expected life ($T^* = 120$ years) referred in literature and the average deviation should be close to zero $c(\xi)$. However, depending on the stairs maintenance conditions, both the $c(\xi)$ assumes zero values, and the $[d(\xi)]^2$ reaches the minimum for the real/observed expected life T^{**} that amounted to 178 (A), 160 (B) and 157 (C) years—Figure 3. The expected life of 10 selected apartment houses elements was thus analyzed for a twofold trend function, i.e., for popular parabolic models (in the previous works) and for one of models searched for with a considerable measure of matching significant determination coefficient R^2 (in presented research).

The results of the modelling when using the non-linear regression method, as well as when using the analysis of variance and residuals for 10 selected elements of tenement houses, are presented in Table 4.

The course of trends of determination coefficients R^2 for 10 selected building elements is presented in the Figure 4. What strikes is exceptional regularity of trends of graphs, no matter what model has been tested: linear, power, exponential, and hyperbolic.

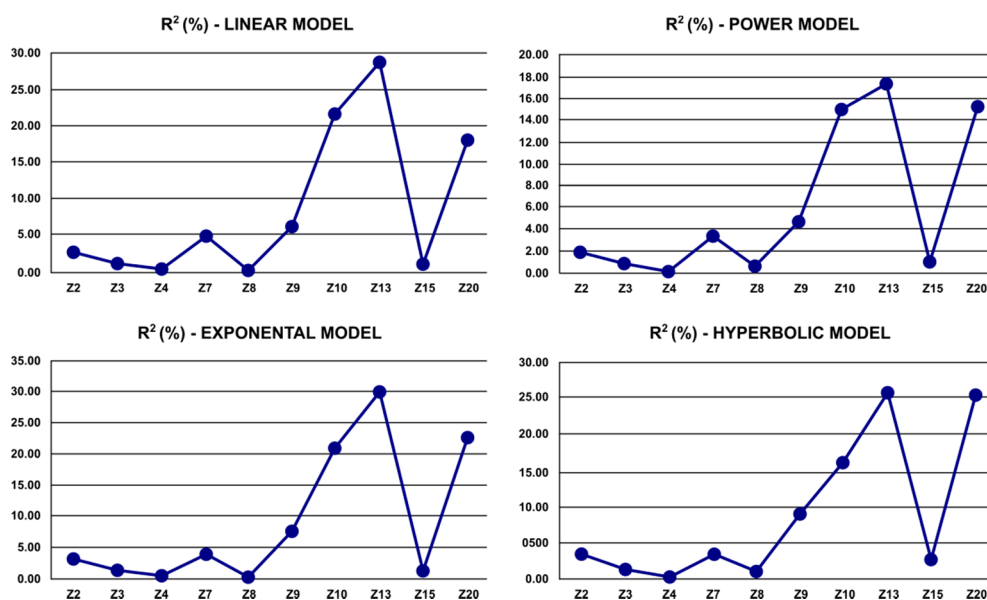


Figure 4. The course of trends of determination coefficients R^2 for 10 selected building elements in linear, power, exponential, and hyperbolic tested models.

3. Discussion

The results of the research presented in the article contain synthetic and analytical model solutions concerning the problems of the technical maintenance and wear of residential buildings with a traditional construction. The cause and effect relationships between the occurrence of damage in the elements of tenement houses (which is treated as an expression of their maintenance conditions) and the size of the technical process of the wear of these elements were determined on a representative and purposefully selected sample of tenement houses that were erected in the second half of the nineteenth and early twentieth centuries in the “Downtown” district of Wrocław.

The age of the elements of an old residential building is of secondary importance with regards to the intensity of the loss of its serviceability value. If we assume that the measure of the adjustment of the mathematical models that were tested using the nonlinear regression method (as a function of the technical wear of building elements over time) is the coefficient of determination, then no more than 30% of the damage to the elements can be explained by the passage of time. Therefore, it is not age that determines the course of the technical wear of the analyzed building components.

The existing theoretical methods of measuring the technical wear of a building and its elements do not reflect the actual state of the wear process over time. The following two facts should be taken into consideration:

- the way of arbitrarily assigning theoretical methods to the building's maintenance conditions, which take into account the age and durability of elements as the only parameters;
- the adopting of too general, and not always appropriate, forms of parabolic and linear functions in order to describe the theoretical side of the progress in the technical wear of building elements over time; among the four new mathematical models that were tested using the nonlinear regression method, none of the power (parabolic) models represent the character of the determined trend of the course of the wear process over time (a very low coefficient of determination and an unnatural size of the parameterized durability); the analysis of variance in the nonlinear regression method also indicates a much better representation of the modelled trend by the exponential and hyperbolic relationships, and a slightly worse representation by linear functions.

The multi-criteria analysis of the proposed mathematical models, which describe the observed states of the technical wear of 10 elements of downtown residential buildings, allowed for the formulation of the following conclusions:

- Regarding mathematical modelling when using nonlinear regression:
 - from the four proposed mathematical models, which were tested using the non-linear regression method, and which describe the observed states of the technical wear of the elements of downtown tenement houses, none of the power models ($Y = AX^B$) represent the nature of the determined trend of the wear process over time (a very low coefficient of determination R^2);
 - analysis of the theoretical wear function $Z_t = f(T)$ shows a much better representation of the modelled trend by the exponential relationships ($Y = \exp(A + BX)$) and hyperbolic relationships ($1/Y = A + BX$), and slightly worse by linear functions ($Y = A + BX$);
 - when assuming that the measure of adjustment of mathematical models to the observed states is the coefficient of determination R^2 , then only in the case of three elements—the roof structure (Z10), window joinery (Z13) and facade (Z20)—was the value of the wear differentiation of these elements (observed in the test) explained by their partial regression (up to 30%) in relation to the age of the analyzed buildings; this observation was confirmed by the acquisition of the largest amount of current data concerning the age of these elements;
- Regarding the analysis of the residual component, and also the assumed parabolic models with regards to the assumed durability T of the elements of downtown residential buildings:
 - durability T , which is defined as the residue variance parameter $[d(\xi)]^2$, and which reaches the minimum at the point of the sought T , takes much greater values than the literature durability T ;
 - the regularity of the results is surprising due to the fact that the variability range of T is narrow and varies from 153 years (for the roof structure Z10) to 177 years (for the massive ceilings above the cellars Z4); for comparison, their literature values are taken as $T = 75$ years (Z10) and $T = 150$ years (Z4);
 - the reliability of the obtained results of the durability T in the analysis of the variance of the residual component was confirmed by the analysis of exponential and hyperbolic models, in which durability T (understood as the period of depletion of the function of the serviceability value ($Z = 100\%$)) assumes values that are similar to those obtained in the analysis of the variance of the residues (this dependence is valid only for elements with a significant coefficient of determination R^2).

The correctness of the assumptions and results of the research in relation to the examined representative group of downtown residential buildings with a traditional construction (erected at the turn of the 19th and 20th centuries) allows for the following statements:

- a. The age of the elements of an old residential building with a traditional construction:
 - is of secondary importance in the process of the intensity of the loss of its serviceability value;
 - is not a fundamental quantity that determines the course of their technical wear.

The nonlinear regression method indicates that, in some specific building elements and with the proposed mathematical models, at best no more than 30% of the damage of elements is explained by the passage of time. Therefore, with the proposed mathematical models, it seems that the age does not determine completely the course of the technical wear of the analyzed building elements.

- b. The degree of the technical wear of the elements of an old residential building is determined by the conditions of its maintenance and use.

4. Summary

The technical maintenance of residential buildings with a traditional construction is, and will be, an on-going problem in the coming years. Therefore, the paper concerns residential buildings dated from the turn of the 19th and 20th centuries, which are part of the downtown development of Wrocław, and which can be seen as an essential link in the process of shaping the cultural and social microenvironment of man. The ability of these buildings to meet the multiple expectations of residents is conditioned by the natural aging of tenement houses, the methods of their maintenance and use, and also the influence of many factors that cause their accelerated wear.

It is worth noting that the discussed quantitative data can provide the basis for programming the size and structure of specialized construction companies that are involved in the maintenance and renovation of residential buildings. These data provide technical information that is necessary for managing buildings and designing the organization of maintenance activities for residential buildings, which determine the quality of the broadly understood maintenance conditions of housings.

Attention should be paid to the individual character of the research results, which were based on the analysis of a homogeneous, coherent group of downtown tenement houses. The transfer of the results of the technical assessment to a different population of residential buildings with a traditional construction should be subjected to great caution and the necessity to conduct surveys. Undoubtedly, such studies should be preceded by the careful and purposeful selection of a typological sample that is representative for the general population.

Such a sample may contain a much smaller number of objects, but it is extremely important that the decisive selection criteria for the initial technical assessment are the elements (or only parts of them) that are essential for the structure (load-bearing structure) of the building. This is especially important when examining composite and complex elements. It can then be assumed that from the point of view of the ultimate limit states of the elements, the degree of their technical wear, which corresponds with the maintaining of the safe and reliable conditions of an object, is equal to 75%.

The methodological aspects of the reliability of the quantitative results of the technical assessment should also aim to minimize the subjectivity of expert judgment in the process of technical examinations of residential buildings by specifying the type, and determining the variability, of at least some of the predicted random influences. It should also be remembered that the issue of technical examinations of buildings, especially residential buildings, needs to be supplemented with full recognition of the forms of their immaterial wear-social and economic. It is a sign of recent times that it is the psychological aspects of the perception of the process of decline in the utility value of flats by their users, supported

by the analysis of the profitability of restoring entire buildings, that play a fundamental role in making decisions about the future of downtown housing developments.

The research should be treated as an exploratory study, the main aim of which was to model cause–effect relationships, which indicate the type and size of damage that expresses the impact of the maintenance conditions of downtown residential buildings on the technical wear of their components. Like any exploratory solution, it should be treated as a multi-criteria recognition of the mechanism of the occurrence and effects of the phenomena that the adjudicator encounters at each stage of the technical assessment of a technical object.

However, this assessment, in its nature, includes an immeasurable (partly subjective) aspect. The construction of a new model of technical research of residential buildings, which is based on the conclusions resulting from the research, will allow the burden of the results of the technical assessment to be moved from the qualitative to the quantitative part. The intention of the authors is that further works related to the broadly understood diagnosis of technical objects should go in this direction.

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