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RESEARCH ARTICLE

The Life Cycle of a Building as a Technical Object

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Abstract

In solving problems associated with maintaining buildings in good condition, it is important to recognise the changes in operational reliability of these buildings over their lifetime. The prediction of reliability of buildings erected in traditional technology is a process requiring multiple generalizations, due to the complexity of their structures, various susceptibility to the influence of external factors, various exploitation practices, and many other issues. One of the simplifications is the perception of the building as a technical object. The presented life cycle of a building is based on the adaptation of mathematical models describing the reliability of mechanical and electronic devices. The article presents the methodology of prediction of operational reliability of a building, and the values of performance features are defined by the parameters of the Rayleigh distribution function.

Keywords

life cycle assessment · service life prediction · reliability

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1 Introduction

In business planning of repairing the buildings one should determine the scope of works. There is no reliable mathematical models that allow the estimation of the operational reliability of a building, often referred to as changes in the building performance. In the case of technical appliances (mechanical and electronic) attempts are undertaken to determine the prediction of their operational reliability, but for buildings – only indicative graphs of changes in performance are presented. The method of behaving and changing the reliability of the building throughout its use will be useful in planning renovations.

All appliances are built from parts. Similarly, each building consists of many components. These elements, which fulfil different functions, are made of dissimilar materials, each has different properties, and different durability periods. In order to determine building reliability it is divided into components which are analysed, first separately and then altogether in the entire building. In the process of predicting the reliability of both individual components of a building and a building as a whole, it may be initially assumed that the lifetime of a building is a 100-year time interval.

To model a situation for the needs of the survival analysis, when the probability changes in time, the Weibull distribution is most frequently used as a distribution of random variable of the time of the building's usefulness. The probability of the exploitation of a building without any breakdowns in a given period of time is defined as exploitation reliability.

2 Background

All technical objects are at risk of damage during the consecutive years of their usage. Reliability of an object is an essential issue during its usage. The main problem is the strive to eliminate damage formation. Predicting the reliability of an object should allow qualitative and quantitative analysis of the possibility of occurrence of unfavourable events.

Issues related to the reliability of technical objects are presented both in the literature on exploitation of mechanical, electrical, electronic appliances and building structures.

Nowak [1], who deals with reliability in the design and analysis of structures, defines reliability as the ability to perform certain requirements (load-bearing capacity, stability, usability, durability, etc.) within an assumed period of usage. He provides indicators of reliability, designed to achieve the appropriate level of the target on an example of bridges. Methods for reliability analysis uncover the real safety reserves in structures.

Frankel [2] defines reliability as probability of non-occurrence of any of the unacceptable ultimate states of a whole structure and its components in the assumed operational period. The reliability of a system is the probability that the system will not fail during a specified time period under given operation conditions, while the risk of failure is the probability that the system will fail during that period and operating conditions.

Also according to Kolowrocki [3] the reliability is defined as the probability of non-occurrence of any damage to a device or a system during its exploitation in time period t, in certain conditions and environ. Unlike quality, reliability is dependent on time - quality is evaluated when an object is being put into use, whereas reliability - during its exploitation period. Reliability is connected with durability which is a measure of the reliability of systems. Kolowrocki defines reliability function Q (t) as the survival function, which decreases with time.

Strauss et al. [4] widely presented issues related to the reliability of building structures. The authors presented a complete historical overview of research on the safety of building structures, explained the levels of assurance of reliability, as well as probabilistic theories and methods of fuzzy safety standards of a structure.

Moan [5] defines reliability in a general context as the ability of a structure to perform the designed functions within a certain time of its exploitation (the condition of a structure) and in mathematical context – as the probability of failure of a structure to maintain certain states within an assumed period of exploitation. The sufficient reliability of a structure is achieved when any damage to an object or an end of its further exploitation result in economically and socially acceptable consequences and when there is sufficiently small probability of any hazards to life and health.

In their works, Sugier, Anders G. [6] presented problems related to exploitation reliability, which she defined as the probability of exploiting a building without any interference (failure) in a given period of time. The author evaluated the construction technologies of residential buildings in terms of their reliability, and buildings erected in traditional technologies occurred to be the best. Emmons, Vaysburd [7] presented the course of the reliability of reinforced concrete structures and also associated problems of repair planning.

The reliability of electronic device, as its specific feature, was presented by Fouchera et al. [8]. The essence of the wear of objects, by C. Cempel, Natke [9] is an increase in damage and partial defects. A prognostic ally elaborated curve of life of a vibro-acoustic machine is based on the reliability of symptoms. Młynczak, Nowakowski [10] analysed the research on the reliability of mechanical objects, mainly vehicles and machines, on the basis of which he developed its own computerised advisory system.

A joint committee of CIB and RILEM has produced a report (by the committee coordinator Masters [11]) which analyses the shortcomings of much 'durability' testing, identifies the problems facing reliable service life prediction, offers a methodology for approaching those problems and lists the key research needs.

A theoretical/conceptual model is developed for Thomsen, Flier [12], which allows for different kinds of obsolescence to be characterized and distinguished. The model distinguishes between physical and behavioral factors and between endogenous and exogenous factors.

Building service life prediction modelling is examined (Grant, Ries [13] to improve the representation of service life in life cycle assessments (LCA) and the evaluation of environmental impacts. A process is developed that incorporates service life, operational energy and LCA modelling which provides a means of examining the effects of materials and systems in building operation, maintenance, repair and replacement.

The object's reliability is defined as the ability to fulfil the task resulting from the purpose it was intended for Nowak, Collins [1], Moubray [14]. It means that the object is demanded to fulfil a determined function in determined time t in determined conditions of operation. The measure of the reliability of an object, in terms of the task, is the probability of the task completing. Such determined reliability measure is a function of time of the building's reliable performance and is called reliability function (Andrews, Moss [15]).

3 Mathematical model of exploitation reliability

To model a situation for the needs of the survival analysis, when the probability changes in time, the Weibull distribution is most frequently used as a distribution of random variable of the time of the building's usefulness [1, 16–21]. The probability density function for the Weilbull distribution is determined with relation:

$$f(t) = \alpha\beta^{\alpha}t^{\alpha-1}exp[-(\beta t)^{\alpha}] \quad for \quad t \geq 0(1) \tag{1}$$

where:

- t the exploitation period,
- α scale parameter (a real number) $\alpha > 0$,
- β the shape parameter (real number), $\beta > 0$.

Parameter α of the distribution determines the probability of a breakdown in time:

- for $\alpha < 1$ the probability of breakdown decreases in time, which suggests that, when the object breakdown is modeled, some specimen may have production defects and slowly fall out of the population,

- for $\alpha = 1$ (exponential distribution) the probability is constant, it indicates the fact that breakdowns are caused by external random events,
- for $\alpha > 1$ the probability grows in time, which suggests that time-related technical wear of elements is the main cause of breakdowns,
- for $\alpha = 2$ (the Rayleigh distribution) the probability grows linearly in time.

Distribution parameter β is a coefficient characterising the rate of the reliability obsolescence:

$$\beta = 1/T_R \tag{2}$$

where T_R denotes the period of the object durability. The distributions function for the Weibull distribution:

$$F(t) = 1 - exp[-(\beta t)^{\alpha}] \tag{3}$$

The distribution function is called the probability of damage, a destruction function, breakdown or a failure function and is determined with the relation:

$$F(t) = P(t < T_R) = 1 - R(t) \tag{4}$$

where:

T_R period of object durability,
$R(t)$ reliability function, also called the probability of proper operation, or durability function.

The intensity of damage λ(t) is a reliability indicator, which is also defined as the intensity of the probability of damage, or the rate of growth of unreliability in relation to reliability [19, 21]:

$$\lambda(t) = \frac{dF(t)}{dt}\frac{1}{R(t)} \tag{5}$$

Exponential distribution is a particular case of the Weibull's distribution, where shape parameter $\alpha = 1$. Exponential distribution is frequently used in the examination of a proper performance time [1, 16, 18, 19, 21]. The characteristic for the exponential distribution is a constant intensity of damage throughout the whole period of the object exploitation $\lambda(t) = \text{const}$. The relation defining the reliability for the i-th component of a building for known parameters α and β may take the form:

$$R_i(t) = exp[-(t/T_{Ri})] \tag{6}$$

Another particular case of Weibull distribution, where $\alpha = 2$ is the Rayleigh distribution. The distribution is a one-parameter distribution, and occurs when the technical wear of the object in time is the main cause of failure. The application of the Rayleigh distribution for buildings seems to be the best choice. All buildings and their components are subject to technical wear and the Rayleigh distribution is applied when the object's wear increases in time. For this case, the reliability function (formula (5)) takes the form:

$$R_i(t) = exp[-(t/T_{Ri})^2] \tag{7}$$

4 Verification of the mathematical model

For the reliability of electronic appliances [10] the intensity of damage depends on wear:

$$S_z = \int_0^t \lambda(t)dt \tag{8}$$

where:

S_z the rate of the product wear.

The technical wear according to the exponential distribution, where the intensity of failure is constant (2) is expressed with a linear function:

$$S_Z = t/T_R \tag{9}$$

where:

S_z the degree of technical wear of an object expressed in percentage,
t the age of the object,
T_R the expected durability period of an object expressed in years.

The obtained relation is one of the time methods applied for the determination of technical wear of carelessly maintained buildings in an arbitrary period of time.

For the Rayleigh distribution, where $\alpha = 2$, $\beta = 1/T_R$, the degree of technical wear equals:

$$S_Z = t^2/T_R^2 \tag{10}$$

The examined material comprises 592 residential buildings performed in the traditional technology, situated within the area of the town of Zielona Gora. The applied building materials and the structural solutions are similar in all the buildings. The masonry walls were made of solid bricks; the floors over the ceilings – masonry, Klein type; the remaining floors – wooden beams; the stairs and the roof structure – wooden, rafter framing – purlin-collar-tie type and in some cases – collar-beam type; roofing – flat tiles or roofing paper.

The technical states of all the buildings were periodically inspected by experts. The periodic monitoring, consisting in the examination of technical wear, resulted in the reports containing the information on the percentage wear of 25 components of the buildings.

For each building element, it is possible to determine the prediction of the technical wear in any arbitrary exploitation period. The durability periods of building elements of determined material-structure solutions are given in, and after substituting them into formulas (9) and (10), the prediction of the degree of technical wear may be obtained according to the exponential distribution and the Rayleigh distribution.

For brick masonry walls, the durability period is determined within the limits 130 – 150 years. The degrees of technical wear were determined for the minimum (130) and the maximum (150) values, with the use of the exponential distribution (formula (9)) and according to Rayleigh distribution (formula (10)). The obtained results are presented in Figure 1.

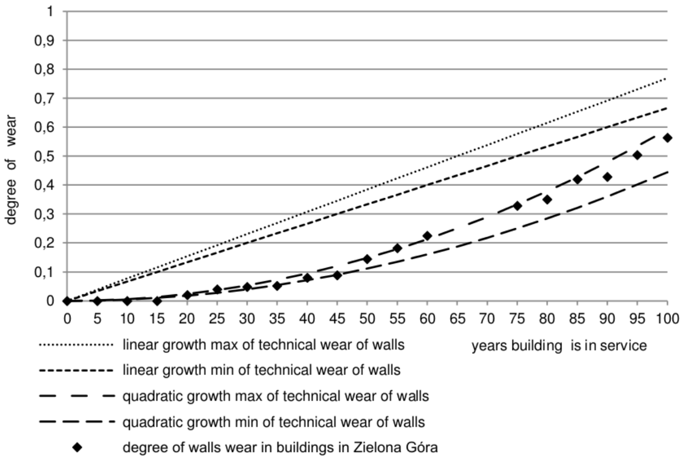

Fig. 1. Predictions of the degree of wear of masonry walls as well as values of the degree of wall wear resulting from the periodic inspection of buildings located in Zielona Gora

The values of the degree of wear of walls by the Rayleigh distribution during a 100-year period of building exploitation, as well as the average values of the degree of wear, obtained in periodic inspections of buildings 5-year, 10, 15, ... 100-year-old, were verified with the use of Student t-test for independent samples. The maximum probability of an allowable error, which could be made while drawing conclusions, was assumed to be equal 0.05. For this level of significance, a critical area was determined. For buildings included in the analysis, the number of degrees of freedom equal to 19, the critical value of the test is $p = 2.0930$. In examining buildings with the t-test, the test result was 2.2957. This value is greater than $p = 2.0930$, which means that the results are statistically significant. It can be assumed, therefore, that the reliability of predictions of buildings determined by the Rayleigh distribution is close to reality.

The prediction of the degree of wear of the walls is an example of the methodology of prediction of technical condition of building elements. In an analogous way, it is possible to elaborate predictive changes in the degree of wear of all building components.

5 Prediction of the technical condition of an entire building

Operational reliability of each object depends on the reliability of its components. However, the reliability of the set of those elements cannot be determined by just calculating their arithmetic mean. Various damage cannot be weighed equally. For example, damage to internal plasters cannot be valued the same as collapsing ceilings, or floors destruction as the failure of a sewage system, etc. The most significant are the components which perform basic functions during use. Other auxiliary components affect the reliability of the object to a lesser extent, and their effect is primarily due to the fact that any damage to auxiliary components may cause changes in the parameters of basic components.

A building constructed in the traditional technology is a system containing dependent and independent components. A complex structure of a building, elements of which form a heterogeneous system, implies the need to decompose the object into subsystems.

The set of all elements is defined by domain of the system, i.e. ordinal numbers from 1 to 25 assigned to individual building elements (e.g., number 1 is the foundation, number 2 – load bearing walls, 3 - partitions, 4 - ceilings, etc.).

A set of links between elements constitute the structure of the system. It is assumed that the decent operation of a residential building is conditioned by the state of all its components, and therefore a dependant serial system was adopted (in a parallel system, it is enough if at least a single element was in a good condition) together with dependant serial subsystems. In an apartment building, damage to some of the elements have an impact on the durability of other elements. In such cases, the reliability of the system is not determined by the reliability of the element itself, but also by the reliability of the associated components.

Due to the impact of damage, a building was assumed to be a dependant system with three types of occurring damage:

- type I – interdependent damage – the system may be damaged as a result of damage to both elements;
- type II – the system may be damaged due to damage to only the first element, or due to damage to two components, the system cannot be damaged due to damage to only the second component;
- type III – the system may be damaged due to damage to only the second element, or due to damage to two components, the system cannot be damaged due to damage to only the first element.

The first element is understood as the element characterized by a greater intensity of damage, the second element – by lesser intensity.

The structure of the proposed system of the object is shown in Figure 2. Given the variety of causes of damage, each time different elements may be damaged. It is possible to assume as many types of building structures as many building destruction may be simulated. A damage scheme occurring most frequently in the examined buildings was selected for further analysis.

Legend of Figure 2:

9 i-th component of a building, $i = 1, 2, \ldots\ 25$,

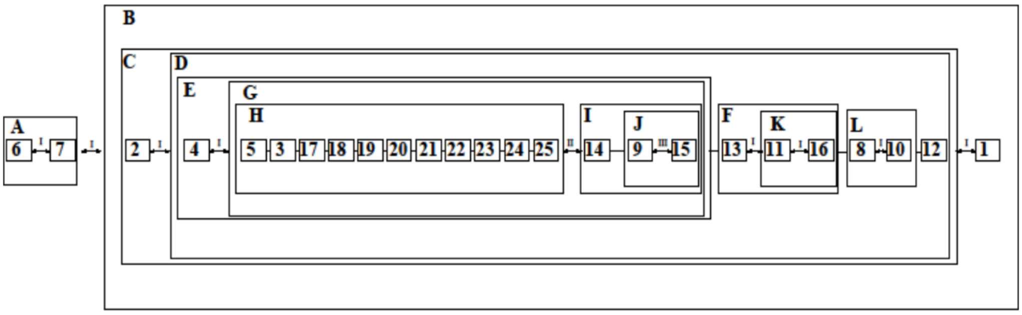

Fig. 2. The structure of the proposed system of an object

A subsystem of an object;
$\longrightarrow$ direction of the damage process;
$--$ serial arrangement of the subsystems.

In the proposed system of the object structure (Figure 2), it was assumed that the main cause of the destruction of the building is a lack of maintenances of covering (element 6) and roof structure (element 7). These elements were selected into subsystem A. The remaining elements of the building are comprised in subsystem B, the proposed structure of which results from the impact of an subserviced element on the damage to others. Subsystem B consists of foundations (element 1) and subsystem C which includes load-bearing walls (element 2) and subsystem D. Subsystem D includes subsystems: E, F, L and door joinery (element 12). Subsystem F consists of glazing (element 13) and subsystem K, which comprises window frames (element 11) together with window painting (element 16). Subsystem L includes gutters and down spouts (element 8) and exterior plasters (item 10). Subsystem E contains ceilings (element 4) and subsystem G consisting of subsystems H and I.

Subsystem H contains partitions walls (element 3), stairs (element 5), kitchens (element 17), stoves (element 18), central heating pipes (element 19), central heating boilers and radiators (element 20), water supply pipes and sewer (element 21), water and sewage fittings (element 22), gas lines (element 23), wiring (element 24), and electrical fittings (element 25). Subsystem I consists of floorings and floors (element 14), and subsystem J which includes plasters (element 9) and paints (walls and ceilings) (element 15).

For the vast majority of cases, it was assumed that damage to the subsystems are mutually dependent, except for subsystems D, H, I. The most frequently proposed type of damage is the mutually dependent type I, which involves damage to the system due to damage to all its elements. It was assumed that the damage to floorings and floors (element 14), internal plasters (element 9), together with their painting (element 15) does not present a significant impact on the destruction of the building. In subsystem G, type II of damage was assumed (the system may be damaged as a result of damage only to the element characterized by a greater intensity of damage, in this case subsystem H, or optionally to both elements). Also a low impact of damage to paints of walls and ceilings was assumed (element 15) on the plaster (element) and therefore subsystem J was proposed to include damage of type III (the system may be damaged as a result of damage only to element which is characterized by a lower intensity of damage, in this case element 9, or alternatively, as a result of damage to both components).

In the case when damage and durability of various elements are mutually independent, the reliability of a subsystem is calculated according to equation:

$$R_S(t) = \prod_{i=1}^{n} R_i(t) \tag{11}$$

where:

$R_S(t)$ reliability of a serial system;
$R_i(t)$ reliability of particular elements of a serial system.

For dependent subsystems, the probabilities of damage were determined for type I with the use of (12), for type II (13), for type III (14), the operational reliability of all subsystems and the entire property - according to formula (15).

$$F_I = qF_1 + (1-q)F_2 \tag{12}$$

where:

F_I probability of damage to a system consisting of dependant elements of type I,
F_1 probability of damage to the first element (subsystem);
F_2 probability of damage to the second element (subsystem);
q probability of damaging the second element earlier than the first one.

$$F_{II} = (1-F_1)F_2 + qF_1 + (1-q)F_1F_2 \tag{13}$$

F_{II} probability of damage to the system of dependant elements of type II, the remaining notations as above.

$$F_{III} = (1-F_2)F_1 + qF_1F_2 + (1-q)F_2 \tag{14}$$

F_{III} probability of damage to the system of dependant elements of type III, the remaining notations as above.

$$F(t) = 1 - R(t) \tag{15}$$

$F(t)$ probability of damaging a subsystem,
$R(t)$ operational reliability of a subsystem.

According to the above relations, operational reliabilities were determined for each subsystem, and finally, for the whole building for the subsequent years of the assumed 100-year period of use. The results of calculations for changes in the reliability of the entire building are shown in Figure 3.

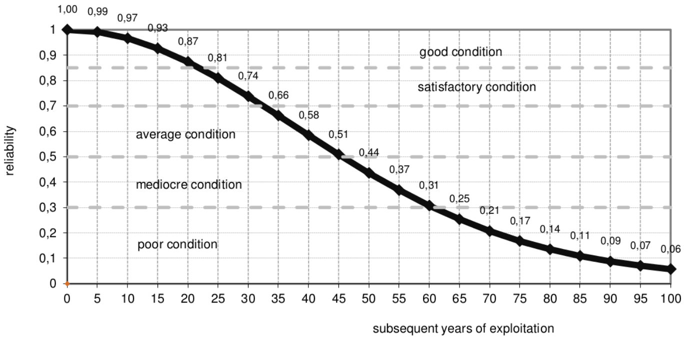

Fig. 3. Changes in operational reliability of a subserviced building

6 Conclusions

The presented changes in operational reliability are the proposition of describing the life cycle of a building. The graph is an example of the changes in the reliability of a subserviced object. While solving problems of the proper use of buildings, five technical conditions may be distinguished: good, satisfactory, average, mediocre and poor. The reliability phases are marked in the figure proportionally to the size of the technical condition. They illustrate the sizes of the results of any changes in reliability. The proposed method for determining the changes in operational reliability is a predictive diagnosis of changes in a building technical condition.

The prediction of the degree of wear of the walls is an example of the methodology of prediction of technical condition of building elements. In an analogous way, it is possible to elaborate predictive changes in the degree of wear of all building components.

The obtained results may be helpful for administrators of residential buildings. Predictive diagnostics is one of the fundamental problems in the process of planning the proper operation of buildings.

References

1 **Nowak A S, Collins K R**, *Reliability of Structures*, McGraw-Hill Int. Edition, 2000.
2 **Frankel E G**, *Systems Reliability and Risk Analysis*, Springer Netherlands, 1984, DOI 10.1007/978-94-009-2776-6.
3 **Kolowrocki K**, *On Limit Reliability Functions of Large Systems. Part I*, In: **Ionescu DC, Limnios N** (eds.), Statistical and Probabilistic Models in Reliability, Birkhauser; Boston, 1999, pp. 153–183, DOI 10.1007/978-1-4612-1782-4_11.
4 **Strauss A, Hoffmann S, Wendner R, Bergmeister K**, *Structural assessment and reliability analysis for existing engineering structures, applications for real structures*, Structure and Infrastructure Engineering, **5**(4), (2009), 277–286, DOI 10.1080/15732470601185638.
5 **Moan T**, *Life-cycle assessment of marine civil engineering structures*, Structure and Infrastructure Engineering, **7**(1-2), (2011), 11–32, DOI 10.1080/15732471003588254.
6 **Sugier J, Anders G J**, *Modelling and evaluation of deterioration process with maintenance activities*, Maintenance and Reliability, **15**(4), (2013), 305–311.
7 **Emmons P H, Vaysburd A M**, *System concept in design and construction of durable concrete repairs*, Construction and Building Materials, **10**(1), (1996), 69–75, DOI 10.1016/0950-0618(95)00065-8.
8 **Fouchera B, Boullie J, Meslet B, Das D**, *A review of reliability prediction methods for electronic devices*, Microelectronics Reliability, **42**(8), (2002), 1155–1162, DOI 10.1016/S0026-2714(02)00087-2.
9 **Cempel C, Natke H G**, *Damage Evolution and Diagnosis in Operating Systems*, In: Safety Evaluation Based on Identification Approaches Related to Time-Variant and Nonlinear Structures, Vieweg Teubner Verlag; Wiesbaden, 1993, pp. 44–61, DOI 10.1007/978-3-322-89467-0_4.
10 **Młynczak M, Nowakowski T**, *Rank reliability assessment of the technical object at early design stage with limited operational data – A case study*, International Journal of Automation and Computing, **3**(2), (2006), 169–176, DOI 10.1007/s11633-006-0169-7.
11 **Masters L W**, *Service life prediction*, Batiment International, Building Research and Practice, **15**(1-6), (1987), 292–296, DOI 10.1080/09613218708726837.
12 **Thomsen A, van der Flier K**, *Understanding obsolescence: a conceptual model for buildings*, Building Research & Information, **39**(4), (2011), 352–362, DOI 10.1080/09613218.2011.576328.
13 **Grant A, Ries R**, *Impact of building service life models on life cycle assessment*, Building Research & Information, **41**(2), (2013), 168–186, DOI 10.1080/09613218.2012.730735.
14 **Moubray J**, *RCM II - Reliability Centered Maintenance*, Oxford, 2007.
15 **Andrews J D, Moss B**, *Reliability and Risk Assessment*, John Wiley, Hoboken, New York, 1993.
16 **Boyen X, Koller D**, *Tractable inference for complex stochastic processes*, In: 14th Annual Conference on Uncertainty in AI (UAI); Madison, WI, USA, 1998, pp. 33–42.
17 **Cordeiro G M, Ortega E M M, Lemonte A J**, *The exponential–Weibull lifetime distribution*, Journal of Statistical Computation and Simulation, **84**(12), (2013), 1–15, DOI 10.1080/00949655.2013.797982.
18 **Khelassi A, Theilliol D, Weber P**, *Reconfigurability analysis for reliable fault-tolerant control design*, International Journal of Applied Mathematics and Computer Science, **21**(3), (2011), 431–439, DOI 10.2478/v10006-011-0032-z.
19 **Nowogońska B**, *Model of the Reliability Prediction of Masonry Walls in Buildings*, Journal of Mechanics Engineering and Automation, **4**(12), (2014), 975–980, DOI 10.17265/2161-623X/2014.12.007.
20 **Walpde R E, Myers R H**, *Probability and Statistics for Engineers and Scientists*, Macmillan Publishing Company; London, 1985.
21 **Zaidi A, Bouamama B, Tagina M**, *Bayesian reliability models of Weibull systems: state of the art*, International Journal of Applied Mathematics and Computer Science, **22**(3), (2012), 585–600, DOI 10.2478/v10006-012-0045-2.