RELIABILITY VERIFICATION OF INDUSTRIAL HERITAGE BUILDINGS

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A number of factories, warehouses, power plants and other industrial buildings have been recognised as industrial culture heritage. At present considerable effort of architects and civil engineers is aimed at re-use of these structures in order to preserve their cultural and heritage value and to avoid wasting energy. However, heritage structures usually do not fulfil requirements of present codes of practice. Simplified conservative procedures of design of new structures given in present codes may lead to expensive repairs and losses of the cultural and heritage value when applied to existing structures. In accordance with EN 1990 and ISO 13822 a probabilistic procedure is proposed to improve the reliability assessment of industrial heritage buildings. The procedure is applied in the reliability assessment of a steel member.

Keywords : *industrial heritage, reliability assessment, probabilistic methods, sustainable development, conversion*

1. Introduction

1.1. General motivation

A number of factories, warehouses, power plants and other industrial buildings has been worldwide registered as industrial cultural heritage. According to the International Committee on the Conservation of the Industrial Heritage TICCIH [1] such structures are mostly of significant architectural, historic, technological or social value. As an example reconversion of the former factory for boiler production built in 1900's in Prague – Karlin is shown in Fig. 1.

Protection (including adaptations and re-use) of the industrial heritage structures is an important issue since it often positively contributes to the sustainable development of urban areas by the following :

- Preservation of cultural values – the heritage value of the structure commonly originates from its uniqueness, quality of craft execution, relationship with an important event or person, urban context, importance as a landmark etc.,
- Recycling of potential resources and avoiding wasting energy,
- Facilitating the economic regeneration of regions in decline.

However, insufficient attention seems to be paid to systematic recognizing, declaring and protecting the industrial heritage in most countries. This is an alarming situation as the lack of attention and awareness of the industrial structures may gradually lead to their extinction.

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Fig.1: Former factory for boiler production in Prague – Karlin under reconversion

When out of use the industrial heritage buildings are degrading and often turning into ruins. Re-use and adaptation of such structures allow for integration of the industrial heritage into a modern urban lifestyle and help protect cities' cultural heritage [2, 3, 4]. These structures are often adapted to become hotels, museums, residential parks, commercial centres etc. as buildings located in city centres profit from available transport network.

Decisions about adequate construction interventions should be based on the complex assessment of a structure. It has been recognised that many heritage structures do not fulfil requirements of present codes of practice. Minimisation of construction interventions is required in rehabilitation and upgrades, but sufficient reliability should also be guaranteed. Application of simplified procedures used for design of new structures may lead to expensive repairs and losses of the cultural and heritage value. In the paper a general probabilistic procedure is thus proposed to improve the reliability assessment of industrial heritage buildings particularly with respect to:

- Better description of uncertainties related to the assessment and
- Facilitating inclusion of results of inspections and tests and the satisfactory past performance of a structure.

Moreover outcomes of the probabilistic assessment can be utilised in a risk-based decision concerning safety measures [5].

1.2. Initiatives concerning protection of the industrial heritage

The protection of the industrial heritage is a multidisciplinary topic including historical, architectonic, civil engineering and ecological aspects. In 1978 the International Committee on the Conservation of the Industrial Heritage (TICCIH) was founded to study, protect, conserve and explain remains of industrialisation. Its recent efforts have resulted in registration of more than 40 industrial sites in the World Heritage List [6].

In the Czech Republic numerous industrial heritage structures were built from 1870 to 1930. It has been recognised that views of Czech architects and civil engineers on protection of the industrial heritage are often considerably different and an important issue may be to achieve consensus on significance of the heritage value [7]. Desired coordinating platform is provided by the Research Centre for Industrial Heritage that maintains a database of the Czech industrial monuments (containing more then 10 000 monuments) and seeks for new uses of the industrial heritage structures.

In addition the Czech Technical University in Prague and the University of Applied Sciences in Ås (Norway) in 2009–2010 participated in the research project focused on the structural assessment of historical immovables, mainly focused on the industrial heritage buildings. Main results of the project are summarised in [4]. General findings of this project are presently improved in a national project DF12P01OVV040, aimed at development of the operational guidelines for structural assessment of the industrial heritage buildings. The guidelines shall be primarily focused on reinforced concrete, steel (iron) and masonry structures.

2. General aspects of the assessment

As a rule re-use and adaptation of the industrial structures require assessment of structural reliability. However, it appears that insufficient attention has been paid by experts to specific issues of the reliability assessment of such structures so far. The following differences between the assessment and design of new structures should be carefully considered:

- Social and cultural aspects – loss of the cultural and heritage values,
- Economic aspects – additional costs of measures to increase reliability of a heritage building in comparison with a new structure (at a design stage cost of such measures is normally minor while cost of strengthening is much higher),
- Principles of the sustainable development – waste reduction and recycling of materials (these aspects may be more significant in case of the assessment),
- Lack of information for the assessment – commonly, testing of the mechanical properties of materials is difficult, expensive, but also very important due to variability of mechanical properties and changes that may have occurred during the working life of a structure (influence of deterioration and damage).

It has been recognised that many heritage buildings do not fulfil requirements of present codes of practice. Minimisation of construction interventions is required in rehabilitation and upgrades, but sufficient reliability should also be guaranteed. Decisions about adequate construction interventions should be based on the complex assessment of a structure considering actual material properties, use and environmental conditions.

Significant uncertainties related to actual material properties and structural conditions usually need to be considered in the reliability assessment of the industrial heritage buildings. In design codes a limited number of safety factors is intended to cover all possible design situations. Therefore, verifications based on deterministic design procedures may be too conservative. Application of commonly used design procedures may thus lead to expensive repairs and losses of the cultural and heritage value. It follows that use of deterministic design procedures may not be an appropriate approach.

It has been recognised that assessment of existing structures is a structure-specific task that is difficult to codify. In accordance with EN 1990 [8] and ISO 13822 [9] a general probabilistic procedure is proposed to improve the reliability assessment of the industrial heritage buildings and allow for inclusion of results of inspections, testing and consideration of the satisfactory past performance.

3. Principles of probabilistic analysis

Probabilistic methods may be useful for the assessment of existing structures where appropriate data can be obtained [5, 10]. Uncertainties that can be greater than in structural design (such as uncertainties related to inaccessible members and connections where construction details cannot be inspected and verified) can be adequately described by such methods [11]. On the contrary, some of the uncertainties reflected (often implicitly) in the load and resistance factors (modelling approximations, deviations from specified dimensions and strengths) may be less than in new construction, particularly when in-situ measurements are taken.

3.1. Specification of models for basic variables

Models for basic variables should be adjusted to the actual situation and state of a structure and verified by inspection and testing. The following principles should be taken into account:

- Material properties should be considered according to the actual state of a structure verified by destructive or non-destructive testing. It may often be appropriate to combine limited new information with prior information. Bayesian techniques provide a consistent basis for this updating; details are provided e.g. in ISO 12491 [12] or in materials of the Joint Committee on Structural Safety JCSS [5,13]. Prior information may be found in normative documents (for example in the Czech National Annex to ISO 13822 [9] where characteristics of different historical materials are provided), scientific literature, reports of producers etc.
- When significant deterioration is observed, an appropriate deterioration model should be used to predict changes in structural parameters due to foreseen environmental conditions, structural loading, maintenance practices and past exposures, based on theoretical or experimental investigation, inspection and experience.
- Dimensions of structural members should be determined by measurements. When the original design documentation is available and no changes in dimensions exist, nominal dimensions given in the documentation may be used.
- Load characteristics should be introduced considering the values corresponding to the actual situation. For structures with significant permanent actions, the actual geometry should be verified by measurements and weight densities should be obtained from tests.
- Model uncertainties should be considered in the same way as at a design stage unless previous structural behaviour (especially damage) indicates otherwise. In some cases model factors, coefficients and other design assumptions may be established from measurements.

It follows that reliability verification of a heritage building should be backed up by inspection including collection of appropriate data. Evaluation of prior information and its updating using newly obtained measurements may be a crucial step of the assessment.

3.2. Probabilistic updating

The failure probability, related to the period from the assessment to the end of a working life t_D, can be obtained from a general probabilistic relationship:

$$p_\mathrm{f}(t_\mathrm{D}) = P\{\min Z[\mathbf{X}(\tau)] < 0 \text{ for } 0 < \tau < t_\mathrm{D}\} = P\{F(t_\mathrm{D})\} \tag{1}$$

where $Z(\tau)$ – limit state function; $\mathbf{X}(\cdot)$ – vector of basic variables including model uncertainties, resistance, permanent and variable actions; and $F(t_\mathrm{D})$ – failure in the interval $(0, t_\mathrm{D})$.

When additional new information I related to structural conditions is available, the failure probability may be updated according to [9] as follows:

$$p''_\mathrm{f}(t_\mathrm{D}|I) = \frac{P\{F(t_\mathrm{D}) \cap I\}}{P(I)} \ . \tag{2}$$

The information should be selected to maximise correlation between the events $\{F\}$ and $\{I\}$. Strong correlation improves the posterior estimate of failure probability while weak correlation yields nearly the same estimates as based on Eq. (1) [11]. The new information may be based on:

1. Inspections that can for instance provide data for the updating of a deterioration model,
2. Material tests and in-situ measurements that can be taken to improve models of concrete compressive strength, steel yield strength, geometry etc.,
3. Consideration of the satisfactory past performance such as survival of a significant overloading,
4. Intensity of proof loading,
5. Static and dynamic response to controlled loading.

In the first two cases the new information is usually applied in the direct updating of (prior) distributions of relevant basic variables that are commonly based on experience from assessments of similar structures, long-term material production, findings reported in literature or engineering judgement. The third case may be very important for the industrial heritage buildings and is described in details in the following. The fourth case is substantially similar to the third one. In the fifth case known structural response to controlled loading can lead to reduction of resistance model uncertainties.

Note that it can be important to consider the satisfactory past performance (the third case) for instance for a structure originally used as a factory that is to be used as a museum or gallery. Such a structure may have resisted to loads much greater than those expected for a future use.

The satisfactory past performance of a structure during a period t_A till the time of assessment may be included in the reliability analysis considering the conditional failure probability $p''_f(t_\mathrm{D}|t_\mathrm{A})$ that a structure will fail during a working life t_D given that it has survived the period t_A. This probability may be estimated in several ways. When the load to which the structure has been exposed during the period t_A is known with negligible uncertainties, the resistance or a joint distribution of time-invariant variables may be truncated (a lower bound is set to the value of load). Using the bounded distribution, the conditional (updated) probability $p_f''(t_D|t_A)$ can be estimated. This approach, similar to the updating for proof load testing described in [5], is illustrated elsewhere [14]. More generally, the updated failure probability may be determined using the following relationship:

$$p_f''(t_D|t_A) = \frac{P\{F(t_D) \cap \bar{F}(t_A)\}}{P\{\bar{F}(t_A)\}} \tag{3}$$

where $\bar{F}$ – complementary event to the failure. The updated probability can be determined by standard techniques for reliability analysis such as the FORM/SORM methods or importance sampling. Updating based on Eq. (3) is applied in a numerical example.

4. Target reliability levels

Reliability verification may be based on the following (equivalent) relationships:

$$p_f''(t_D|I) < p_t\ , \qquad \beta''(t_D|I) = -\Phi^{-1}[p_f''(t_D|I)] \geq \beta_t \tag{4}$$

where p_t – target failure probability; Φ^{-1} – inverse cumulative distribution function of the standardised normal variable; and β_t – target reliability index.

The target reliability level can be taken as the level of reliability implied by acceptance criteria defined in proved and accepted design codes. The target level should be stated together with clearly defined limit state functions and specific models of basic variables. ISO 2394 [15] provides examples of the target reliability indices for the anticipated life-time period, related to different relative costs of safety measures and failure consequences, see Tab. 1.

Relative costs of safety measures	Consequences of failure			
	Small	Some	Moderate	Great
High	0	1.5	2.3	3.1
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

Tab.1: Target reliability index (life-time, examples) in accordance with ISO 2394

Depending particular conditions the consequences of structural failure may include [16]:
- Cost of repair or replacement,
- Economic losses due to malfunction,
- Societal consequences (costs of injuries and casualties),
- Losses of the cultural and heritage values,
- Unfavourable environmental effects (CO_2 emissions, energy use, release of dangerous substances),
- Psychological effects (loss of reputation).

In common cases an investigated structure or its member is associated with failure consequences given in Tab. 1 using expert judgement. Some guidance on the classification can be obtained from EN 1990 [8] where examples of civil engineering works for three Consequence Classes are provided. However, the inconsistency in classes of failure consequences (four in ISO 2394 [15] and three in EN 1990 [8]) may somewhat complicate the judgement.

Upgrade costs normally consist of :
- Costs related to surveys, design and directly to structural upgrades, and if relevant for an investigated structure also of:
- Losses of the cultural and heritage values,
- Economic losses due to business interruption,
- Replacement of users etc.

A limited guidance on the assessment of relative costs of safety measures is provided in the committee draft of revision of ISO 2394 (to be issued in May 2015). Therein relative cost of improving life safety is classified with respect to the ratio between the costs C_1 related to safety measure and the costs C_0 of design and construction costs. The following indicative values may be considered for different relative costs of improving life safety :
- High : $C_1/C_0 = 0.1$,
- Normal : $C_1/C_0 = 0.01$,
- Low : $C_1/C_0 = 0.001$.

For the industrial heritage buildings moderate consequences of failure and moderate costs of safety measures can often be assumed. In this case ISO 2394 [15] indicates $\beta_t = 3.1$. It is worth noting that other standards such as EN 1990 [8] and ISO 13822 [9] provide different target reliability levels, classified with respect to the failure consequences only. However, the costs of safety measures may become an important aspect in case of the industrial heritage structures.

Yet none of aforementioned standards explicitly takes into account the cultural heritage value of a structure. To the best knowledge of the authors, the only model accounting for the cultural heritage value is a simple empirical relationship proposed in [17] :

$$p_t = \frac{S_c\, t_D\, A_c\, C_f}{n_p\, W} \times 10^{-4} \tag{5}$$

where :
- S_c – social criterion factor (recommended value for listed historical buildings 0.05),
- t_D – remaining working life (considered as 50 years); Ac = activity factor (recommended value for buildings 3),
- C_f – economical factor (5 for a moderate consequences, recommended values : 10 for not serious and 1 for serious consequences of failure),
- n_p – number of endangered persons (the most favourable and unfavourable estimates $n_{p,min} = 1$ and $n_{p,max} = 10$, respectively, are considered for significant risk of injury or fatalities – a middle class of consequences [18]), and
- W – warning factor (1 – sudden failure without previous warning).

Considering these indicative data, lower and upper estimates of the target reliability level are obtained from Eq. (5) :

$$\begin{aligned} p_{t,max} &= \frac{0.05 \times 50 \times 3 \times 5}{1 \times 0.3} \times 10^{-4} \approx 3.8 \times 10^{-3} \ , \quad \beta_{t,min} = 2.7 \ , \\ p_{t,min} &= \frac{0.05 \times 50 \times 3 \times 5}{10 \times 0.3} \times 10^{-4} \approx 3.8 \times 10^{-4} \ , \quad \beta_{t,max} = 3.4 \ . \end{aligned} \tag{6}$$

It appears that the target reliability is within the broad range from 2.7 to 3.4. The value recommended in ISO 2394 [15] is approximately in the middle of this range.

It is interesting to indicate the target reliability levels for a structure with the same characteristics entering Eq. (6), but the social criterion factor S_c. For a structure not listed as the historical building, the factor $S_c = 1$ might be assumed. Then, Eq. (5) yields:

$$\begin{aligned} p_{t,max} &= \frac{1 \times 50 \times 3 \times 5}{1 \times 0.3} \times 10^{-4} \approx 7.6 \times 10^{-2}\ , \quad \beta_{t,min} = 1.4\ , \\ p_{t,min} &= \frac{1 \times 50 \times 3 \times 5}{10 \times 0.3} \times 10^{-4} \approx 7.6 \times 10^{-3}\ , \quad \beta_{t,max} = 2.4\ . \end{aligned} \tag{7}$$

It follows from Eqs. (6) and (7) that the target reliability index for the heritage building should be greater (by about one) than that for a similar structure not listed as a historical building. Whether this is an adequate increase of reliability is a complex question that should be investigated individually by a supplementary investigation. In such an investigation it should be taken into account that an increase in the target reliability may potentially result in losses of the cultural heritage values. More detailed information on the procedures for assessment of the target reliabilities for existing structures is provided in [16, 19].

5. Design of construction interventions

If the structure does not satisfy reliability requirements, construction interventions may become necessary. When dealing with preservation of the industrial heritage buildings, it may be difficult to propose construction interventions that respect all requirements for preservation of the cultural heritage value. Modern principles of investigation and interventions seem to include the following aspects:

- Minimisation of intervention to a historic place, unobtrusiveness and respect of the original conception (for instance when a structure is valued for its contextual and associative values, preservation of its equipment is not needed),
- Respect for the integrity of heritage buildings and avoidance of methods that might entail a loss of authenticity,
- Safety of the construction,
- Durability of materials (but use of original materials is mostly not required),
- Balance between cost and available financial resources.

6. Numerical example

The proposed procedure is applied in the example of reliability assessment of a steel member of a 100-year old building registered as the industrial heritage. The building, originally built as a part of a textile mill, will be used as an office building. The selected structural member is exposed to bending moment due to permanent and imposed loads. An anticipated working life is 50 years. Note that the reliability assessment is considerably simplified to illustrate general steps of the probabilistic verification rather than to describe case-specific details.

Initially, reliability of the member is verified by the partial factor method. Characteristic values of the resistance and permanent action, given in Tab. 2, are specified considering results of on- site surveys and original design documentation. During the previous use of the structure, degradation has resulted in loss of the steel section. In the following assessment the actual steel section characteristics are considered and no further degradation is expected

Variable	Sym.	Unit	Dist.	x_k	μ_X/x_k	V_X
Bending resistance	R	kN/m	lognormal	5.18	1.19	0.08
Permanent load effect	G	kN/m	normal	3.06	1	0.05
Imposed load effect (50 y.)	Q	kN/m	Gumbel	3	0.6	0.35
Effect of the load that the structure has survived	S	kN/m	normal	3.3	1	0.05
Resistance uncertainty	K_R	–	lognormal	1	1.0	0.05
Load effect uncertainty	K_E	–	lognormal	1	1	0.1
x_k – characteristic value; μ_X – mean; V_X – coefficient of variation.						

Tab.2: Models for basic variables

during the remaining working life. Characteristic value of the imposed load is determined in accordance with EN 1991-1-1 [20].

The deterministic verification reveals that reliability of the member is insufficient as the actual resistance is approximately by 40 % lower than required by Eurocodes.

Probabilistic reliability analysis is based on the limit state function for the member exposed to bending :

$$Z(\mathbf{X}, t) = K_R\, R - K_E\, [G + Q] \tag{8}$$

where K_R – model uncertainty of resistance; R – flexural resistance; K_E – model uncertainty of load effects; G – permanent action; and Q – maxima of the imposed load related to a reference period. The considered characteristic values and probabilistic models of the basic variables based on recommendations in [13, 21] are given in Tab. 2. For convenience all the basic variables in Tab. 2 are normalised by $L^2/8$ (L is a span of the member).

It is noted that the accepted mean value of the model uncertainty for a flexural resistance $\mu_{KR} = 1.0$ differs from the mean value reported in [22] where $\mu_{KR} \approx 1.15$ is obtained by the statistical evaluation of test results. For assumptions made in the design of new structures, actual resistance is positively influenced by tolerance specifications in dimensions of a rolled sections and the mean of the model uncertainty increases. However, the assessment of the existing beam is based on actual dimensions and this positive effect vanishes.

The reliability verification is firstly based on Eq. (1) (no new information). Using the FORM method, the reliability index is low, $\beta \approx 1.3$. Considering the target reliability levels indicated in Section 4, the reliability of the member seems to be insufficient.

Secondly, the reliability is updated considering the satisfactory past performance to improve this estimate. It is known from previous performance of the structure that the member has survived the load S equal to 1.1-times the characteristic value of the imposed load. Uncertainties in the survived load effect are described by the normal distribution with the mean equal to the observed value and coefficient of variation 0.05 . Given the survival of the load S, the updated reliability index $\beta''(t_D|S) \approx 2.7$ follows from the conditional failure probability based on Eq. (3) :

$$p''_f(t_D|S) = \frac{P\{[K_R\, R - K_E\, (G + Q) < 0] \cap [K_R\, R - K_E\, (G + S) > 0]\}}{P\{K_R\, R - K_E\, (G + S) > 0\}} \;. \tag{9}$$

It appears that the predicted reliability is still rather low. In general four options can now be discussed with a client:

1. To upgrade the member,
2. To propose an adequate limit on the imposed action,

3. To accept a shorter remaining working (such as 15 years) and after that re-assess the beam,
4. To derive optimum target reliability following the principles provided of ISO 2394 [15].

Note that the second option may be applicable for industrial plants or bridges rather than office buildings. When the third option is accepted the updated reliability index $\beta''(15\,y|S) \approx 3.1$ is obtained from Eq. (9) using 15-year maxima of the imposed load. This reliability level might be acceptable (see Section 4). The fourth option is thoroughly discussed in [16] where optimisation of the total costs related to a structure including potential failure consequences and human safety criteria are considered.

To generalise findings of the probabilistic analysis, a parametric study is conducted for the ratio of the characteristic values of S and Q. Fig. 2 indicates the difference $\Delta\beta$ between the updated and not updated reliability index (Eqs. (9) and (8), respectively) as a function of the ratio s_k/q_k. To illustrate the effect of updating for various reliability levels, the difference $\Delta\beta$ is plotted in Fig. 2 for four values of the not updated reliability index ($\beta = 1.3$ obtained previously, $\beta = 2.3$, 3.1 and 3.8 that correspond to the target reliabilities for moderate relative costs of safety measures given in Tab. 1). The different β-levels are simply obtained by hypothetical increases of the mean resistance by about 22 %, 48 % and 75 % for $\beta = 2.3$, 3.1 and 3.8, respectively.

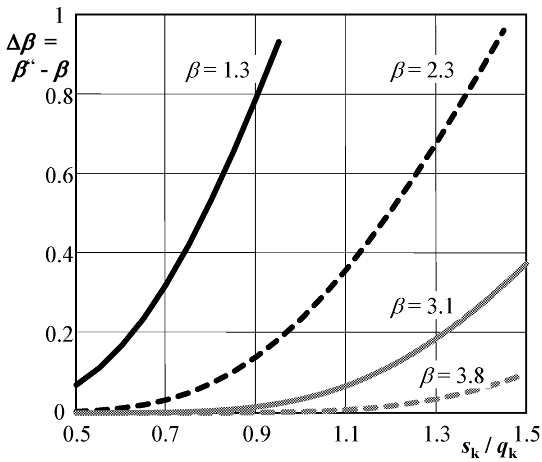

Fig.2: Variation of the difference $\Delta\beta$ with the ratio s_k/q_k for $\beta = 1.3$, 2.3, 3.1 and 3.8

It follows from Fig. 2 that the difference $\Delta\beta$ between the updated and not updated reliability index increases with the load ratio s_k/q_k, i.e. with increasing significance of the survived load S. The difference $\Delta\beta$ is more significant for the lower reliability levels $\beta = 1.3$ and 2.3 and less significant for the higher reliability levels $\beta = 3.1$ and 3.8.

It can be also shown that the effect of the updating increases when variable actions are less important and reliability is primarily dependent on time-invariant variables [23].

7. Concluding remarks

Protection of the industrial heritage buildings helps preserve cultural values, avoids wasting energy and facilitates economic regeneration of regions in decline. Present insufficient attention to systematic recognizing, declaring and protecting the industrial heritage may, however, lead to their extinction.

Reliability verifications of the industrial heritage buildings should be backed up by inspection including collection of appropriate data. Assessments based on simplified conservative procedures used for structural design may lead to expensive repairs and losses of the cultural and heritage value.

Probabilistic methods can thus be applied to better describe uncertainties and take into account results of inspections and tests as well as satisfactory past performance. Target reliability levels are primarily dependent on the costs of safety measures and consequences of failure including loss of the cultural heritage value.

Numerical example reveals that the difference between the updated and not updated reliability index increases with increasing the survived load S to which the structure already resisted. The effect of the updating is more significant for the lower reliability levels.

Acknowledgements

This study is an outcome of the research project DF12P01OVV040 'Assessment of safety and working life of industrial heritage buildings', supported by the Ministry of Culture of the Czech Republic. The paper is an extension of a recent conference contribution [24].

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Received in editor's office: September 3, 2012
Approved for publishing: May 16, 2014