Evaluation of the Load-bearing Capacity of Timber Members in Existing Structures based on Information from a Qualified Investigation in situ within a Stepwise Procedure

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Abstract Enhanced knowledge from a qualified survey in situ can help to model the load-bearing behaviour of an existing structures more realistically by considering specific knowledge on material parameters and conditions. A semi-probabilistic evaluation format with partial safety factors is used in common practice. Standardised options to include specific information into the design concept have to be worked out. These are improved strength grading using non-/semi-destructive means and adjustments within the safety concept itself. However, for everyday practice two problems arise. It is often not possible to determine strength parameters but reference properties like Young's modulus or density. Besides, an exhaustive determination of material parameters is cost-intensive and therefore often not possible for smaller projects. This contribution presents a procedure to include data gained in a qualified survey in situ into the design concept for the verification of load-bearing capacities of existing timber structures. The level of detail of the design format is increased stepwise considering the level of detail of the survey. These levels are named Knowledge Levels in accordance with the Science and Policy Report of the Joint Research Centre (JRC) from 2015. Knowledge Level 1 includes the evaluation based on current Eurocodes without adjustments. Knowledge Level 2 is divided into three sub-levels including adjustments of partial safety factors for target values derived for existing structures, an improved strength grading based on non-/semi-destructive technical means and the updated of the partial safety factor for the material strength based on measured reference properties. Knowledge Level 3 includes a probabilistic evaluation comparing the actual reliability of the current design situation with and without parameter update.

Keywords: timber, existing structures, evaluation procedure, semi-probabilistic safety concept, partial safety factors

1 Introduction

The challenging task of investigating and evaluating existing structures has been addressed several times in current research work. These studies range from non-/ semi-destructive investigation techniques in situ to probabilistic aspects to analyse and update the reliability of an existing structure. To evaluate the load-bearing capacity of an existing structure, its structural elements have to be investigated in detail. This embraces the aspects illustrated in Fig. 1 from (Lißner & Rug, 2015).

The figure shows that for the investigation and evaluation of timber structures, numerous issues have to be studied in detail. To investigate these aspects named, different techniques and technical means are available and under continuous development and improvement. An overview concerning investigation techniques to be applied in situ can for example be studied in (Dietsch & Köhler, 2010), (Kasal & Tannert, 2011) and (Lißner & Rug, 2015).

The attempt to standardise the investigation and evaluation of existing structures has been dealt with mainly on a national level. To be named here are for example the Italien standards UNI 11119 (UNI, 2004a) and UNI 11138 (UNI, 2004b), the Swiss standard SIA 269 (SIA, 2011) and the German Leaflet (DBV, 2013). In (Perria & Sieder, 2019) and (Loebjinski et al., 2019b) the current state of the art concerning the investigation and evaluation of existing timber structures as given in codes, standards and selected research work is summarised.

On an international level work has been carried out to standardise national approaches, e.g. in (European Commission, Joint Research Centre, 2015) independent from the building material. A European standard for the investigation of existing timber structures has been developed lately, EN 17121 (CEN, 2017). However, whereas this standard provides a common approach for the investigation, no methods for an adjusted evaluation of the load-bearing capacity and serviceability including data collected in a qualified survey in situ are provided. For concrete, advices are given on an international level by the Fédération Internationale du Béton (fib) (FIB, 2016). For timber, no standardised methods considering the special material properties of this natural grown and thus inhomogeneous material are available at state.

This contribution illustrates a proposal that has been worked out so far and summarizes the results of the research that has been carried out for the steps of the evaluation. This contribution focusses on the modification of the semi-probabilistic evaluation concept. For more detailed information on non- and semi-destructive investigation techniques available for timber, the interested reader may refer to the literature.

Existing Structures		
Cross sections	Material parameters	
• Size • Adherence of minimum cross sections • Influence on the load-bearing capacity • Influence on the serviceability	• Timber species • Density • Strength • Young's modulus • Moisture content • Number/ location of knots • Core and sapwood • Cracks	Grading & strength class obtained from decisive criteria of DIN 4074-1 DIN 4074-5
Structure/ Structural system	Bracing	
• Date of erection • Load history/ load assumption • Static system/ changes • Geometry, cross sections, connections • Deformations • Alterations of positions of elements	• Construction principle • Sufficiently existent • Effective and including connections • Influence on the load-bearing capacity • Sufficient load-bearing capacity and serviceability	
Connections		
• Type, material strength • Load distributions • Serviceability • Type of damage • Load-bearing capacity • Structural facts influencing the load-bearing capacity and serviceability		

↓

Evaluation of the load-bearing capacity and serviceability	
Evaluation of the static and structural functionality	
Load-bearing capacity	Serviceability

↑

Damages			
Cracks		Deformations	
• Depth • Length • Static relevant/ irrelevant		• Size • Influence on the load-bearing capacity • Influence on the serviceability	
Insects and fungi		Corrosion	
• Type • Amount of damage • Influence on load-bearing capacity • Reconstruction measures • Treatment measures	Timber protection investiga-tion	• Type • Amount of damage to timber & connections • Influence on load-bearing capacity and serviceability	Investigation of cor-rosion (e.g. corro-sion of tension cracks for steel, maceration for tim-ber)

Fig. 1 Aspects for the evaluating of load-bearing capacity and serviceability of timber structures in existing buildings from (Lißner & Rug, 2015)

2 Proposal for an Evaluation Procedure

Whenever the evaluation of the load-bearing capacity of a structural element in an existing structure becomes necessary (e.g. due to load changes or structural damage), current design codes have to be applied to evaluate its sufficiently load-bearing behaviour. At state, it is not possible within the concept of the Eurocode, to include updated information on a critical member that can be gained through a qualified and detailed investigation in situ. However, as the decision on the amount of information gathered in situ based on e.g. material tests always aims for an optimal allocation of time and resources considering sufficient structural safety, it always forms a very individual optimisation problem of the task at hand. Thus, this research does not aim to replace current practice but to provide suggestions for its enrichment. Therefore the presented procedure is built on current practice providing methods to be applied if necessary or desired. The proposal is illustrated in Figure 2 as presented in (Loebjinski et al., 2019a) and developed further in (Loebjinski, Rug & Pasternak, 2019) and described in more detail hereinafter. This contributions summarizes results of different updating steps that have been presented bevor and informs about some recently developed achievements and open challenges as well as open research questions. The abbreviation *KL* stands for *Knowledge Level*, which is based on JRC Science and Policy Report 2015 (European Commission, Joint Research Centre, 2015).

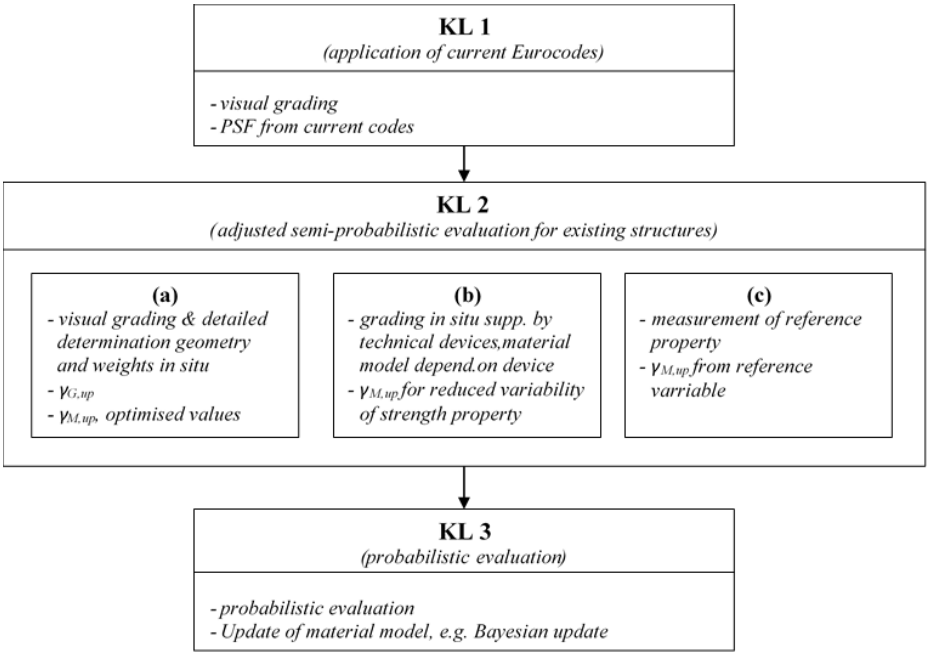

Fig. 2 Framework for the evaluation of the load-bearing capacity of existing structures (Loebjinski, Rug & Pasternak, 2019)

3 Evaluation in Knowledge Level 1

This level represents the current state of the art applying EN 1990, EN 1991 and EN 1995 to analyse the structural behaviour and check sufficient structural safety. Partial safety factors (PSF) to be applied are summarised in Table 1.

Table 1 Partial Safety Factors from EN 1990 (CEN, 2010a), EN 1995 (CEN, 2010b) & EN 1995/NA (CEN, 2010c)

γ_G	γ_Q	Code	γ_M		Code
Permanent act.	Variable act.		Solid Timber	Glulam	
1.35	1.50	EN 1990	1.30	1.25	EN 1995-1-1
			1.30	1.30	NA for GER

This concept is well developed and applicable for a variety of practical problems. However, the safety elements for a semi-probabilistic evaluation do not allow for a consideration of updated information concerning load and material parameters and is thus rather less flexible. Especially for existing timber structures a skilled selection, treatment and arrangement of structural elements are important to ensure that structures are reliable und durable. What is more, the grading of the material is often performed only by visual inspection, whereas grading supported by technical devices can significantly enhance knowledge about the material properties of the elements at hand, see e.g. (Sandomeer & Steiger, 2009), (Kessel & Sandoz, 1989), (Sandoz, 1989), (Linke, Rug & Pasternak, 2019). This information shall be used by introducing a Knowledge Level 2 in the suggested approach.

4 Evaluation in Knowledge Level 2

4.1 General Remarks

This level embraces different options for an adjusted semi-probabilistic evaluation of existing structures. Current Eurocodes form the basis of structural design and verification of load-bearing capacity. EN 1990 (CEN, 2010a) allows a probabilistic evaluation. However, the semi-probabilistic path is chosen in practice in most common cases, see Figure 3 from (CEN, 2010a). Optional, but not part of current versions of Eurocodes, are deterministic methods (method a). They are often part of older code formats and may be applicable to evaluate existing structures as e.g. permitted in Germany by (Fachkommission Bautechnik der Bauministerkonferenz (ARGEBAU), 2008).

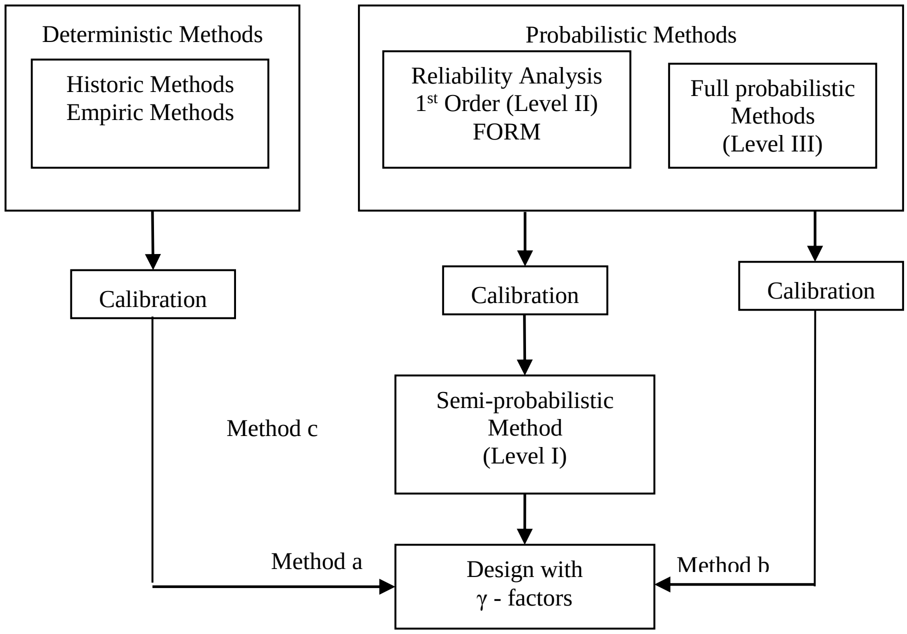

Fig. 3 Overview of methods of reliability analysis from EN 1990 Annex C (CEN, 2010a)

The following sections summarize research work performed to update the semi-probabilistic design concept for the evaluation of existing structures. Case studies have been used to test the applicability of the developed concepts and presented in (Loebjinski, Linke & Rug, 2019) and (Loebjinski et al., 2019c).

4.2 Evaluation in Knowledge Level 2a

In this level, the evaluation of the load-bearing capacity can be done with modified PSF for the material strength without directly updating the material parameters by technical means, but by a more qualitative evaluation. These factors are based on an adjusted target reliability level for maintenance measures in existing structures.
In ISO 2304:2015 target reliability indices are given considering consequences of failure and relative cost of life safety measures, see Table 2 from (ISO, 2015).
In ISO 2394 (ISO, 2015) it is emphasized, that these values have been determined considering economic optimisation and may be not acceptable concerning life safety risks. For existing structures, (Vrouwenvelder, 2002) suggests to move from medium to large relative costs of safety measures.

Table 2 Tentative target reliabilities related to one year reference period and ultimate limit states, based on monetary optimization, from (ISO, 2015)

Relative cost of safety measure	Consequences of failure					
	Class 2		Class 3		Class 4	
Ref. period	T_{ref} = 1a	T_{ref} = 50a*	T_{ref} = 1a	T_{ref} = 50a*	T_{ref} = 1a	T_{ref} = 50a*
Large	3.1	1.7	3.3	1.8	3.7	2.7
Medium	3.7	2.7	4.2	3.2	4.4	3.5
Small	4.2	3.2	4.4	3.5	4.7	4.2
* The value has been calculated statistical independency of following years						

The association of consequence classes given in Table 2 to the consequence classes of EN 1990:2010-12 Annex B is not straight forward even though both documents contain descriptions and examples for types of structures within different classes. Within EN 1990:2010-12 Annex C three classes are described whereas ISO 2394:2015 contains four classes of failure consequences. However, SIA 269:2011, the Swiss code for existing structures, contains the target reliabilities indicated in Table 2 indicated with *low consequences of failure* (equals values in *class 2*), *moderate consequences of failure* (equals values in *class 3*) and *high consequences of failure* (equals values in *class 4*). (Steenbergen et al., 2015) suggest to reduce the target reliability for existing structures based on the target value for new structures by $\Delta\beta = 0.5$ and for a minimum reliability index by $\Delta\beta = 1.5$. The JRC Science and Policy Report 2015 (European Commission, Joint Research Centre, 2015) indicates reliability indices for four consequence classes $\beta = 1.8$ (CC 0), $\beta = 1.8$ (CC 1), $\beta = 2.5$ (CC 2) and $\beta = 3.3$ (CC 3) for a reference period of 50 years. What is more, target reliability indices for CC 2 and CC 3 are illustrated depending on the affected area in case of collapse.
ISO 13822:2010 (ISO, 2010) which contains guidelines for the assessment of existing structures refers to ISO 2394 (ISO, 2015) for underlying principles of reliability analysis. Here, guidance to calculate partial safety factors with fixed sensivity factors is given. What is more, fib bulletin no. 80 (FIB, 2016) describes two options to adjust partial safety factors for existing structures with fixed sensivity factors. These are the *Design Value Method* (DVM), which is also described in ISO 2394:2015 and the *Adjusted Partial Safety Factor Method* (APFM). The former allows a direct calculation of PSF with fixed sensivity factors and adjusted target reliability whereas the latter allows the calculation of factors to adjust given PSF for different requirements.

The determination of PSF with fixed sensivity factors is a good, straight forward method. However, studies showed that especially for variable actions the current value of $\gamma_Q = 1.5$ cannot be verified very easily and does not seem to fit for different kinds of variable actions, see e.g. (Grünberg, 2004) (Loebjinski, Rug & Pasternak, 2017). Thus, optimised PSF for different requirements have to developed as an optimisation problem. These are under preparation within this research project. These values are optimised as they are only valid for different categories of measures as indicated in Table 3 and different design situations, e.g. uniaxial strain induced by permanent action and live load. Similar studies have been published e.g. by (Fischer, 2010) for reinforced concrete and by (Stauder, 2015) for structures of hydraulic engineering. Parameters studies indicated a great scatter of the reliability among different design situations, see e.g. (Baravalle, 2017), own studies support this. A high sensivity of the coefficient of variation of the material strength could be observed.

4.3 Evaluation in Knowledge Level 2b

In this level information gained by a grading supported by technical devices is available. Thus, the strength class can be updated. To generated a trustful result, different grading methods should be combined, i.e. visual grading ultrasonic measurements, extraction of core samples etc. By these means, and updated strength class can be determined, which is often higher than solely by visual grading, see e.g. (Linke, Rug & Pasternak, 2019).
The accuracy of grading significantly influences the material model in a strength class, see e.g. (Faber, Köhler & Sørensen, 2004). In former studies it has been investigated, if the material model can be updated based on the grading technique applied. In (Loebjinski, Rug & Pasternak, 2019) the stochastic grading model by (Pöhlmann & Rackwitz, 1981) has been applied on test results from (Linke, Rug & Pasternak, 2019). It has been figured out, that the results depends on the timber species. For oak samples an improvement of the material model and reduction of the coefficient of variation (cov) of the assumed prior model could be observed, the results for softwood also depend on the timber species. The prior model was assumed based on (JCSS, 2006). Baysian update has been applied to investigate the influence of the results of the calibration tests to update the prior model. Thus, an updated material model for different grading techniques could not be developed with certainty yet.
It has been figured out, that the assumption of a reduction of the variability of strength properties in a test based on different grading techniques is critical applying this model, as the uncertainty of the tests themselves has to be considered. Besides, it was identified, that multiple correlation coefficients to combine different parts of information are needed, see e.g. (Linke, Rug & Pasternak, 2019). Current studies including multiple regression analysis of different grading parameters gave good to very good results, see (Linke, Rug & Pasternak, 2020).
However, as the reliability and the calibrated PSF γ_M is highly sensitive against changes of the coefficient of variation cov_x of the material strength, this value has been studied. It is defined in Eq. (1)

$$\mathrm{cov}_x = \frac{\sigma_x}{\mu_x} \tag{1}$$

where σ_x is the standard deviation and μ_x is the mean value of the variable x. It was assumed that with higher strength classes cov_x is reduced as the mean value increases and the standard deviation can be assumed equal in different strength classes. This was approved by the calibration test. Thus, high strength classes support a reduction of the PSF γ_M, although this is still difficult to quantify as this depends on the timber species.

4.4 Evaluation in Knowledge Level 2c

If it is decided to carry out material tests in situ, the PSF to be applied on the target variable (e.g. bending strength) can be updated based on the correlation relation of target variable and measured reference variable (e.g. Young's modulus from ultrasonic measurement). In (Loebjinski et al., 2019a) a formula has been developed to update the PSF γ_M based on a measured reference property. The updated PSF $\gamma_{m,up}$ (see Eq. (2)) without and $\gamma_{M,up}$ (see Eq. (3)) including model uncertainty is

$$\gamma_{m,up} = \exp\left(\frac{cov_{y,target} \cdot \sqrt{1-\rho_{x,y}^2}}{1+\rho_{x,y} \cdot cov_{y,target} \dfrac{x_{meas} - \mu_{x,ref}}{\mu_{x,ref} \cdot cov_{x,ref}}} \cdot \left(\alpha_R \cdot \beta + \Phi^{-1}(q) \right) \right) \tag{2}$$

$$\gamma_{M,up} = \gamma_{Rd} \cdot \gamma_{m,up} \tag{3}$$

with $cov_{y,target}$ the cov of the target variable y, $cov_{x,ref}$ the cov of the reference variable x, $\mu_{x,ref}$ the mean value of the reference variable x, $\rho_{x,y}$ the correlation coefficient, α_R the sensivity factor of the material resistance ($\alpha_R = 0.8$ from EN 1990:2010-12), β the target reliability, q the quantile for the definition of the characteristic value of the target variable used for design ($q = 0.05$) and γ_{Rd} the model factor that should be calculated from a normal distribution and the 50%-quantile considering the adjustment for a non-dominant variable (see EN 1990:2010-12 or ISO 2394:2015).
This results applying this approach have to be evaluated carefully, as they only refer to information based on one measured reference variable, which can differ locally. Thus, it does not release the engineer from a detailed investigation and careful evaluation of results.

5 Evaluation in Knowledge Level 3

As indicated above, EN 1990 which is the basis for current design concept of the Eurocodes, allows for probabilistic methods to verify sufficient structural safety. However, target values of the reliability index are still under discussion. In (Baravalle & Köhler, 2017) it was figured out, that the reliability level differs significantly between different design situations depending on load shares and types of (variable) loads. What is more, the target value of $\beta = 3.8$ for a reference period $T_{ref} = 50a$ seems not entirely match the reliability level of current codes. What is more, target values for existing structures considering an enhanced knowledge and sufficient structural performance are not given
ISO 2394:2015 (ISO, 2015) gives target reliability indices depending on the relative costs of safety measures and consequences of failure.

This principle is also included in SIA 269:2011, the Swiss code giving guidelines for the evaluation of existing structures. This allows for the decision on an individually chosen target reliability. In this relation, (Vrouwenvelder, 2002) suggest to move for existing structures into the range of high costs of safety measures.
Another approach is the distinction into minimum (disapproval) and target reliability (reconstruction) level as e.g. given in NEN 8700. Values are also discussed for example in (Diamantidis, Holický & Sýkora, 2017).
Knowledge Level 3 includes an update of the material model, e.g. by Bayes Updating. It seems to be more appropriate to evaluate the reliability of a design situation and study the effects of changes of the random variable for the case at hand to indicate possible structural measures rather than to compare the result to a fixed target value. As mentioned above, the reliability level of different design situation differs depending on the type of loading, load shares and assumptions for material parameters.

6 Conclusion

The evaluation of the load-bearing capacity of an existing structure is fundamentally different compared to the design of new structures. The availability of information to update load and material parameters due to the existence of the former in tangible form is a big advantage. However, the quantification and utilisation of different forms of information in structural design is also a challenge. Thus, the major part of work consist of the development of standardised approaches (statistical methods, adjusted semi-probabilistic methods)) within a flexible and widely applicable format, that is being approved by the building authorities. An attempt to structure different options has been presented in (Loebjinski, Rug & Pasternak, 2019), see Figure 4.
Figure 4 illustrates the parts of work and processes carried out within the research project and tries to structure ideas on how to combine information. However, these are some attempts without claiming to be complete. A lot of knowledge concerning statistical methods, good technical devices, a well based code format and expert knowledge experienced engineers and architects are already existent. All these fields need to be combined to satisfy the special requirements and challenges when evaluating existing structures. Thus, a lot of further work is necessary to develop good and practicable tools to include different types of information about an existing structure into its evaluation.

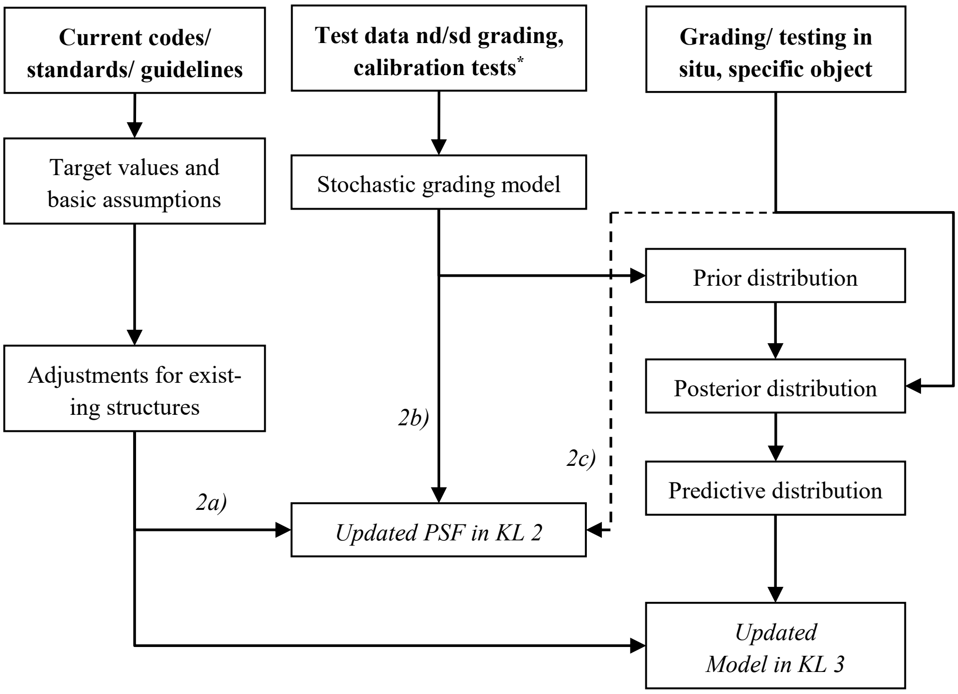

Fig. 4 Schematic updating procedure, extended from (Loebjinski, Rug & Pasternak, 2019)

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